NASA/CR—2003-212521

# Aero-Propulsion Technology (APT)
## Task V—Low Noise ADP Engine Definition Study

V. Holcombe
United Technologies Corporation, Pratt & Whitney, East Hartford, Connecticut

October 2003

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V. Holcombe
United Technologies Corporation, Pratt & Whitney, East Hartford, Connecticut

Prepared under Contract NAS3–25952

National Aeronautics and
Space Administration

Glenn Research Center

October 2003

Note that at the time of research, the NASA Lewis Research Center was undergoing a name change to the NASA John H. Glenn Research Center at Lewis Field. Both names may appear in this report.

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# Preface

This report was delivered to NASA as an informal document. There were three engine noise studies done by the Allison Engine Company (now Rolls Royce), General Electric Aircraft Engines and Pratt & Whitney in preparation for the Advanced Subsonic Technology (AST) Noise Reduction Program. The objectives of the studies were to identify engine noise reduction technologies to help prioritize the research that was subsequently done by the AST Program. The reports also summarize the predicted performance and economic impact of the noise reduction technologies.

The emphasis of commercial turbofan research during the early 1990's was on higher bypass ratio engines. While the technology insertion into service has been slower than expected, many of the results from these studies will remain valid for a long period of time and should not be forgotten by the aerospace community. In 2003, NASA decided to publish all three studies as Contractor Reports to provide references for future work. The quality of the reproduction of the original report may be poor in some sections.

Dennis L. Huff
Chief, Acoustics Branch
NASA Glenn Research Center

FOREWORD

This report presents the results of a study conducted to identify noise reduction technologies to be proven in subscale model testing for an economically competitive propulsion system that will permit greater capacity operation of the air transportation system. This study was conducted as Task V under the Aero-Propulsion Technology (APT) program, NASA Contract NAS3-25952, under the direction of Mr. Kal Abdalla, Project Manager.

The NASA Task Manager for Task V is Robert Jeracki, NASA Lewis Research Center and Mr. V. Holcombe served as Task Manager for Pratt & Whitney. Acknowledgements are given to the following principal investigators for their efforts in the following areas:

| | |
|---|---|
| Marlin DeVries/Roy Behlke | - Fan Aero |
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| Mary Sweetman | - Performance |
| Uudo Tari | - Technology Programs |
| Robert Owens | - Mission Analysis |
| Jon Marx | - Design |

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

# SUMMARY

A study was conducted to identify and evaluate noise reduction technologies for Advanced Ducted Propeller (ADP) propulsion systems that would allow increased capacity operation and result in an economically competitive commercial transport. The study was conducted as Task V - Low Noise ADP Engine Definition Study as part of the Aero-Propulsion Technology Program under NASA Contract NAS3-25952 which is to provide aero-propulsion support encompassing a wide range of technologies for future civil and military, subsonic and supersonic air breathing vehicles. The goal of the Task V study was to investigate the aero/acoustic/structural advancements in fan and nacelle technology required to match or exceed the economic benefits and fuel burned savings of a constrained diameter large Advanced Ducted Propeller (ADP) compared to an unconstrained ADP propulsion system, with a noise goal of 5 to 10 EPNDB reduction relative to FAR 36 Stage 3 at each of the three measurement stations -- namely, takeoff (cutback), approach, and sideline.

To achieve the program goal, a second generation ADP was selected to operate within the maximum nacelle diameter constraint of 160" to allow installation under the wing. When compared to the baseline ADP, the second generation ADP has a slightly higher cruise FPR (1.35 vs 1.36), a reduction in fan tip speed of 25%, resulting in a noise benefit of 14 EPNdB cumulative margin relative to Stage 3. The means for further reducing noise to meet the goal of 30 EPNDB cumulative margin have been identified and suggested technology programs have been proposed to accomplish this goal. The large reduction in fan tip speed was obtained by utilizing the benefits of advanced rotor casing treatment, vaned passage casing treatment (VPCT), and advanced low distortion inlet technology offering a potential 3% improvement in fan stage efficiency.

To study the impact of fan and nacelle technologies of the second generation ADP on fuel burn and direct operating costs for a typical 3000 nm mission, a large, twin engine commercial airplane simulation model was developed which evaluated concepts of a 95K thrust class ADP. This airplane has 340 seats in a 3-class configuration, a design range of 6500 nm, a MTOGW of approximately 650,000 lbs, and a 0.83 cruise Mach number. The engine was scaled to meet airplane thrust requirements and the airplane's MTOGW was varied to meet design range requirements. The evaluation showed that the second generation ADP has advantages in TSFC, weight, and drag over current ADP technology while meeting the 160-inch nacelle diameter constraint. In comparison to current conventional turbofans, the second generation ADP has a fuel burn advantage of 15.2% which could result in an annual savings of 628 million gallons of fuel for the airline industry.

The major emphasis of this study focused on fan blade aero/acoustic and structural technology evaluations and advanced nacelle designs. In the compressor area, two technologies, advanced casing treatments and reduced inlet distortion, were evaluated to reduce fan tip speed and fan generated noise along with two configuration changes, swept fans and 3-dimensional fan exit guide vane (FEGV) shapes, which were also identified as having acoustic potential. The low noise fan designs were analyzed using solid titanium whose low bending and torsional frequencies created tuning and stall flutter concerns which were eliminated by the use of composite construction methods. Results of this study showed that advanced casing treatment, swept rotors, and 3-D FEGV's will contribute toward reduced fan tip speed, reduced noise level, and improved performance of a second generation ADP engine.

For the second generation ADP designs, model testing of the components are required. The interactive performance of these components, along with noise characteristic, requires verification by wind tunnel testing utilizing an advanced Interaction Rig.

## INTRODUCTION

Recent studies indicate that major airports in the nation's air transportation system face a serious problem in providing greater capacity to meet the ever increasing demands of air travel. This problem could be relieved if airports are allowed to increase their operating time now restricted by curfews and by relaxing present limits on takeoff and landings. The key operational issue in extending the present curfews is noise.

The objective of this study is to identify the noise reduction technologies which will allow increased capacity operation and result in an economically competitive propulsion system.

This study investigated the aero/acoustic/structural advancements in fan and nacelle technologies required to match or exceed the economic benefits and fuel burned savings of a constrained diameter large Advanced Ducted Propeller (ADP) compared to an unconstrained ADP propulsion system, with a noise goal of 5 to 10 EPNDB reduction relative to FAR 36 Stage 3 at each of the three measurement stations -- namely, takeoff (cutback), approach, and sideline. Major emphasis focused on fan blade aero/acoustic and structural technology evaluations that led to definition of specific technology verification plans. The technologies selected are to be proven in subscale model testing that will lead to larger demonstrator engine tests in the mid 1990's.

## TECHNOLOGY SELECTION

### STUDY APPROACH

The second generation ADP engine definition study was based on a broad PW/NASA data base (Figure 1). This data base included acoustic, performance and reverse tests conducted in 1989-90 in 17" rig size at the United Technologies Research Center (UTRC). Further fan performance testing in 32" rig size was conducted at P&W's Willgoos Laboratory.

A cooperative (NASA/P&W) test program was initiated in 1989, testing P&W's 17" rig in the LeRc 9' x 15' and 8' x 6' tunnels. Other programs include installation testing of the P&W 17" rig at NASA-Langley with a moving ground plane simulation in 1992 and a ADP demonstration engine test to be conducted at NASA Ames 40' x 80' tunnel. In addition to these test programs, a LeRc sponsored 17" rig inlet flow-through test was conducted at UTRC in late 1991.

The data base generated from the early model test programs was applied to this study effort. Component technologies required for a low noise, ADP propulsion system were identified for verification testing in a high horsepower 22" interaction rig at LeRc. These programs are an integral part of a broad, long term subsonic technology program supported by NASA.

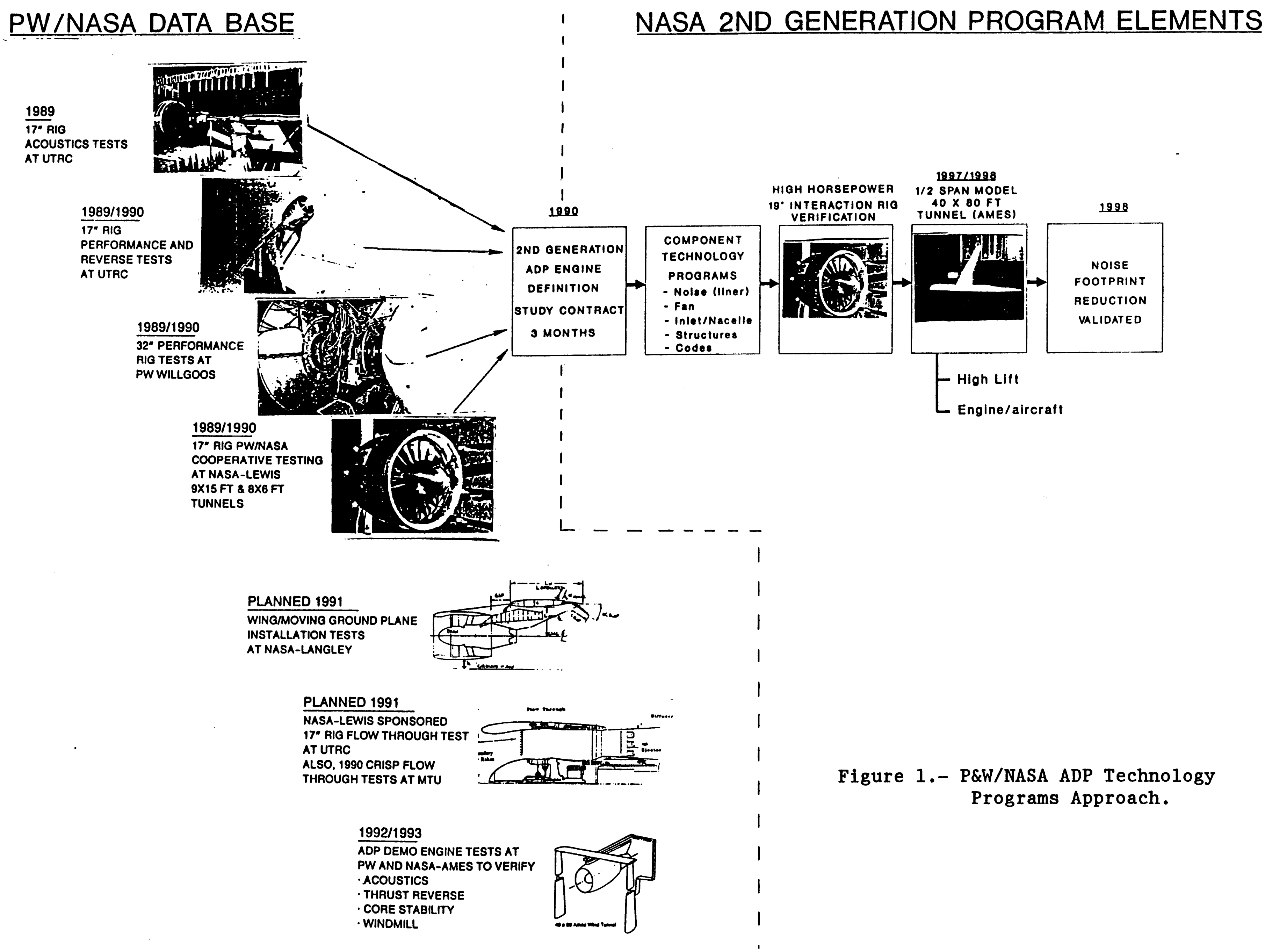


Figure 1.- P&W/NASA ADP Technology Programs Approach.

## ENGINE CYCLE SELECTION

### Baseline ADP

To assess the benefit of advanced technology, a current technology ADP engine was used as baseline. This ADP engine has 1.35 FPR at cruise, 140" fan tip diameter and powers a large over-the-water twin jet transport with 90,500 pounds of sea level static takeoff thrust. However, with current technology, the noise level of this baseline cycle has nominal Stage 3 compliance.

### Advanced Technology ADP Cycle

A new ADP cycle with advanced technology, a second generation ADP, was selected to achieve the noise reduction target within the maximum nacelle diameter constraint of 160" to allow installation under the wing. The new cycle has a slightly higher cruise FPR (1.36) than the baseline ADP, and the fan tip speed has been reduced 25%, resulting in a noise benefit of 14 EPNdB cumulative margin relative to Stage 3.

The large reduction in fan tip speed was obtained by utilizing the benefits of advanced rotor casing treatment (VPCT) and advanced low distortion inlet technology. VPCT also offered a potential 3% improvement in fan stage efficiency. Table I compares the current and advanced technology ADP cycles.

TABLE I.- ADP CYCLES AT CRUISE

| | Current Technology | Advanced Technology |
|---|---|---|
| Fan Pressure Ratio | 1.35 | 1.36 |
| Fan Corrected Tip Speed, ft/sec | 1190 | 862 |
| Fan Stage Efficiency, % | base | +3% |
| Fan Tip Diameter, in. | 140 | 143.1 |
| Cumulative EPNdB Margin Relative to Stage 3, dB | 0 | 14 |

### Performance Benefit

The TSFC benefit of advanced technology in the ADP is due to increased fan efficiency. It is also of interest to compare the ADP's, both current and advanced technology, to a conventional turbofan. The STF940 engine (Ref. 1) is a conventional turbofan with 1.65 FPR at cruise and was used for TSFC and economic comparisons. The TSFC comparison of the current technology ADP, the advanced technology ADP, and the conventional STF940 turbofan is shown in Figure 2. The current technology ADP in Table 1 has been adjusted to the same diameter and fan pressure ratio as the advanced ADP to remove the effect of cycle difference. The advanced technology ADP has a 14.2% improvement in TSFC relative to the current technology turbofan STF940.

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Reference 1. Owens, R. E., Hasel, K. L., and Mapes, D. E., "Ultra High Bypass Turbofan Technologies for Twenty-First Century". AIAA Paper No. AIAA-90-2397, 1990.

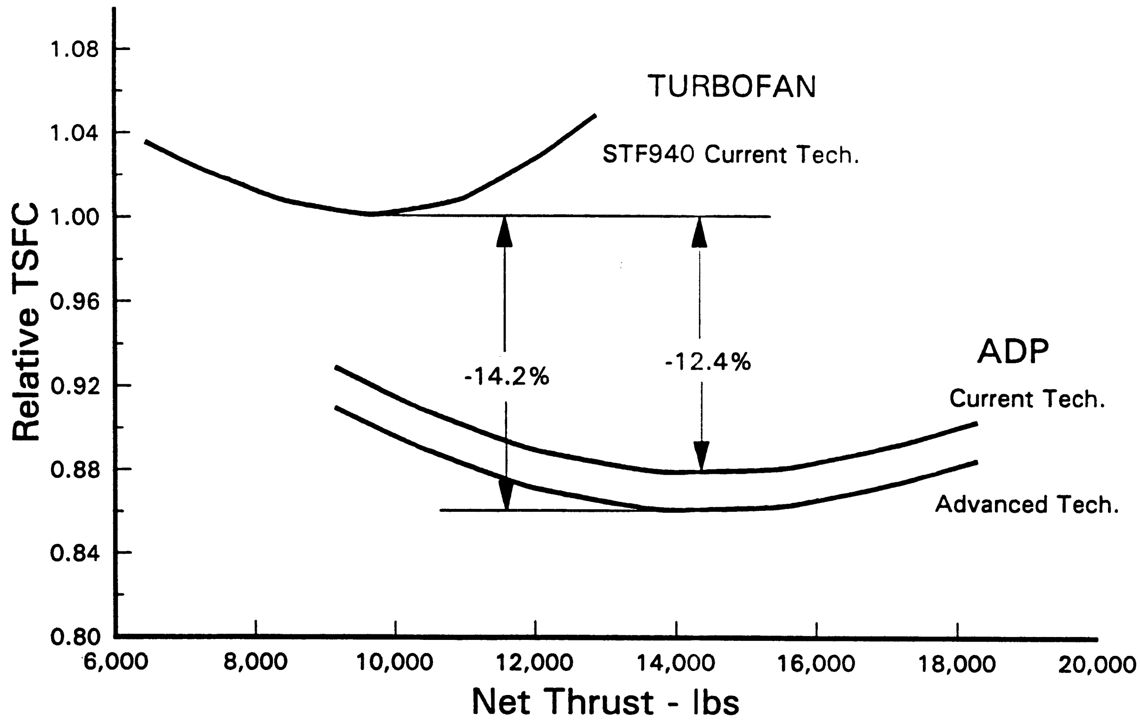



Figure 2.- Fuel Performance Comparison (35K/.8M/Std Day/Uninstalled).

## COMMERCIAL TRANSPORT SIMULATION

### Low Noise ADP Study Fuel Burn and DOC Analysis

A large twin engine commercial transport simulation was developed to evaluate study concepts of a 95K thrust class ADP. This airplane has 340 seats in a 3-class configuration, a design range of 6500 nm, a MTOGW of approximately 650,000 lbs, and a 0.83 cruise Mach number. Influence coefficients were generated from this model to study the impact of fan and nacelle technologies on fuel burn and direct operating cost (DOC) for a typical 3000 nm mission. In generating these influence coefficients, the airplane and engine were assumed to be "rubber"; the engine was scaled to meet airplane thrust requirements and the airplane's MTOGW was varied to meet design range requirements. Scaling criteria and the influence coefficients are shown in Table II.

### Second Generation ADP vs Current ADP Technologies

The second generation ADP has advantages in TSFC, weight, and drag over current ADP technology while meeting the 160-inch nacelle diameter constraint such as shown below:

- 2.1% TSFC reduction from fan efficiency
- 6.2% reduction in propulsion weight
- 8.9% reduction in nacelle drag
- 4.2% reduction in nacelle diameter.

TABLE II. - SECOND GENERATION ADP ADVANTAGES OVER CURRENT ADP TECHNOLOGY

Scaling Criteria

1. Engine Thrust Scaling
   - 10000 ft takeoff field length (SL/+27F)
   - 300 ft/min ROC @ 33,000 ft/0.83M
   - Climb to 33,000 ft in 200NM @ MTOGW (most critical)
   - Climb to 33,000 ft in 30 minutes @ MTOGW

2. Engine Price Scaling: $105/lb of thrust

3. Airframe Price Scaling: $120/lb of OEW

4. Engine Weight Scaling: Rel. wt = $ESF^{0.922}$

5. Nacelle Drag Scaling: Rel. Drag = $ESF^{0.920}$

6. TSFC Scaling: Rel. TSFC = $ESF^{-0.038}$

7. Engine MMC Scaling: Rel. MMC = $ESF^{0.3}$

8. Engine MLC Scaling: Rel. MLC = $ESF^{0.1}$

Influence Coefficients

Large Twin Transport/ADP Powered Rubber MTOGW, 340 Passengers
Scaled Engines, Base ESF = 0.972/3000 NM Mission
1990 Dollars, $1.00/Gallon Fuel Price

| Influence of | Block Fuel (%) | DOC+I (%) |
|---|---|---|
| +1% TSFC | 1.43 | 0.53 |
| +1000 lbs/eng | .76 | 0.38 |
| +10 lbs drag/eng @ 35K 0.8M | .11 | 0.04 |

The weight evaluation includes impact of VPCT, reduced fan tip speed, and nacelle diameter, but does not include the impact of bowed stator vanes.

Producing the required thrust level with current ADP technology exceeds the nacelle diameter constraint by 7" posing another advantage of second generation technology. Second generation ADP technologies show a 4.6% improvement in fuel burn and a 2.0% improvement in DOC+I over current ADP technolgy due to:

| | Block Fuel | DOC+I |
|---|---|---|
| o TSFC | -3.0% | -1.1% |
| o Propulsion Weight | -1.0% | -0.5% |
| o Nacelle Drag | -0.4% | -0.2% |
| o Nacelle Diameter(impact to airframe) | -0.2 | -0.2 |
| Total | -4.6% | -2.0% |

These improvements could translate to an annual savings to the airline industry of 190 million gallons of jet fuel and $340 million in direct operating cost, assuming a successful aircraft production run of 500 aircraft.

## Second Generation ADP vs Conventional Turbofans

The STF940 represents a current day conventional turbofan. For the STF940 to have equal payload/range as an ADP powered aircraft, the MTOGW will need to be increased to 705,000 lbs. Thrust requirements of a turbofan powered large twin commercial transport are thus greater than the ADP. The STF940 needs to be scaled 125% putting it in the 108K thrust class to meet the thrust requirements. The technologies in the second generation ADP puts the ADP's fuel burn advantage at 15.2% ahead of current day turbofans due to the factors listed below. Relative to today's turbofans, the annual savings in jet fuel would be 628 million gallons for the airline industry.

| | Delta Fuel Burn (%) |
|---|---|
| o TSFC | -18.0 |
| o Propulsion Weight | +2.1 |
| o Nacelle Drag | +0.7 |
| Total | -15.2% |

# TECHNOLOGIES EVALUATION

## COMPRESSOR AERO

Two technologies were defined which will allow a reduction in fan tip speed and fan generated noise; advanced casing treatments and reduced inlet distortion. Two additional configuration changes, swept fans and 3-dimensional FEGV (Fan exit guide vane) shapes, were identified as having performance and acoustic potential. The areas of investigation conducted under the aero design determined the performance and operability potentials of these advance technology items and the test programs needed to quantify the benefits are discussed in the following paragraphs.

### Aero Design

#### Parameter Selection

The Low Noise ADP Engine Definition Study identified an engine cycle, fan flow and pressure ratio required for a desired thrust for an engine constrained to a nacelle diameter of 160 inches. A detailed analysis was conducted and a flowpath was selected based on aerodynamic and geometric ground rules. To assure efficient operation over the entire engine operating range and allow for inlet boundary layer blockages, the maximum corrected fan flow in the operating range was limited to a specific flow of 45. lb./(sec.*ft2), which corresponded to the max. climb thrust operating point. Fan blade gap/chord ratio was a compromise between blade weight, blade forward and reverse flow operability margin and passage shape for surface Mach number control. Additional design considerations that helped to establish the flowpath included a spherical fan tip to allow uniform tight clearance at all pitch angles; a root slope of 7° or less for reverse pitch without hub interference; a core inlet which was radially recessed behind the fan root for minimal dirt and hail ingestion; and an elliptical spinner with 0° slope at the fan root to provide a desired radial flow distribution entering the fan.

Mechanical design requirements for fan case containment hardware and fan case tip stability treatment resulted in establishment of 143.1" as the fan tip leading edge diameter for a 160" nacelle outer diameter. The fan blade count was set at 16 based on earlier studies with consideration of attachment bearing surface, blade weight and containment, airfoil aspect ratio, engine length and reverse pitch interference. The root diameter was established based on requirements for fan face flow area and variable pitch mechanism hardware which resulted in a fan with a .39 hub/tip diameter ratio.

The FEGV was stacked 10° axially rearward at the tip to provide maximum blade/vane spacing, the FEGV count was based on acoustic cutoff of tones and thickness was based on structural load sharing.

<u>Flowpath</u>

Given the above fan diameter information and based on experience from first generation ADP designs, a fan flowpath for the study was developed. Figure 3 shows the resultant engine cross section and fan flowpath used for streamline analysis.

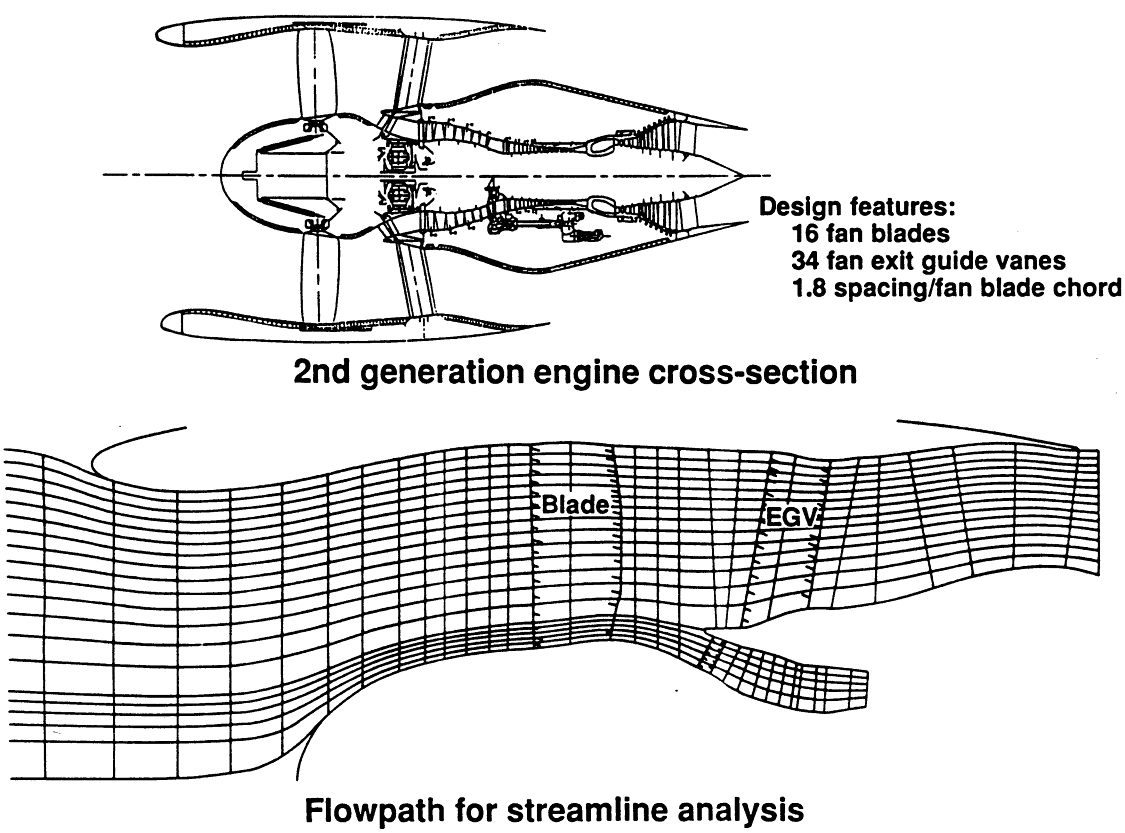
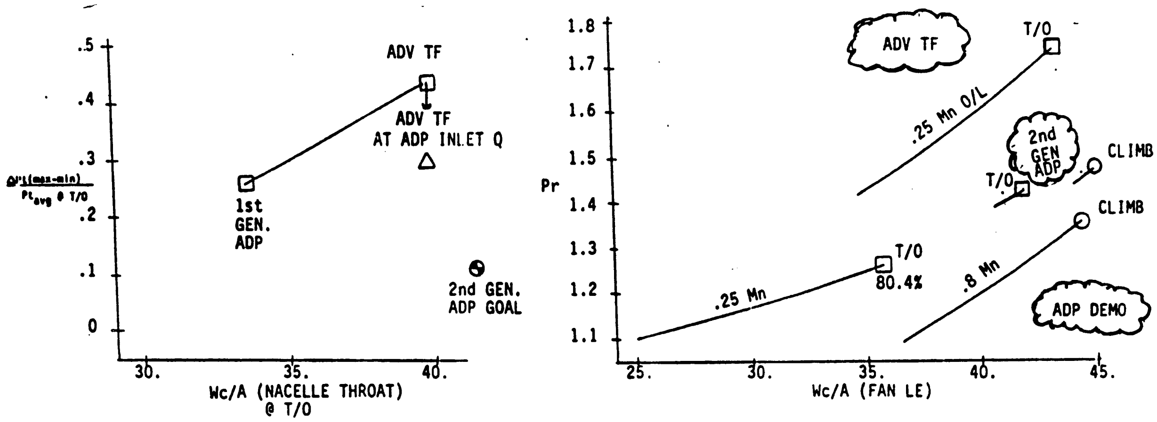



Figure 3.– NASA Second Generation ADP Study.

## Baseline Tip Speed

For the given fan pressure ratio, an extensive study was conducted to determine the level of fan loadings and tip speeds that would result for a current technology (baseline) fan. Due to the constrained nacelle diameter and smaller fan area, a higher cruise pressure ratio is needed relative to an unconstrained diameter cycle at the same thrust. Similarly, the constrained diameter forces the takeoff inlet specific flows up 16% which raises the distortion produced by the inlet at high angles of attack. Figure 4 shows the cycle relationship for different pressure ratio fans. Table III shows a comparison resulting from the study between a constrained and unconstrained current technology ADP fan. Required tip speeds were set based on the level of inlet distortion that the fan is subjected to plus a minimum required margin.




*Separated Nacelle - Loss Comparisons*

*Comparison of T/O match points on high vs low BPR cycles*

**Higher Total pressure ( $\Delta P$ ) inlet distortion results from the higher specific flow (Q) at the nacelle throat - $\Delta P/Q$ remaining approx. constant.**

Figure 4.- 17" ADP Rig Test Results Show a Greater Inlet Distortion at Takeoff for the Increased W/A of the Second Generation ADP Relative to Current Fans if Current Inlet Technology is Employed.

TABLE III. - NASA SECOND GENERATION ADP STUDY

| | First Gen. ADP (TS30) | | Constrained Diameter ADP Twin Current Technology |
|---|---|---|---|
| Rotor Tip Diameter | ~160" | | 140" |
| Inlet Hub/Tip | 0.426 | | 0.4 |
| Pressure Ratio - Cruise | 1.29 | | 1.35 |
| Flow/Area - Cruise | 42.5 | | 42.5 |
| - T/O | 36.0 | +16% → | 41.7 |
| Corr. Tip Speed - Cruise | 953 | +25% → | 1190 |
| Constant SM - T/O | 963 | +34% → | 1290 |
| Efficiency - Cruise | Unconstrained Base | | -1.5% |
| (Duct Stage) - T/O | Unconstrained Base | | -4.0% |

Notes:
1) The constrained diameter large twin engine cycle drives the first generation ADP to a higher tip speed and flow/area.
2) Without technology advances, efficiency and noise penalties will result.

The inlet AOA distortion levels were predicted for the respective cycles. Baseline fan speeds were set for loading levels with a smoothwall rubstrip fan case. Minimum stability requirement was determined to be 6-8% surge margin and was established based on experience for engine build variations, fan tip clearance wear limits, and pylon induced back pressure distortion.

### Advanced Technology Operability

Technologies were considered that would allow a reduction in fan tip speed to reduce acoustic noise levels as well as technologies that would raise the performance levels of the 2nd generation ADP's. Two technologies that concentrated on reducing noise via lower fan tip speeds were based on first generation testing and included advanced fan tip casing treatment and reduced inlet distortion at AOA (Table IV). The first generation ADP technology demonstrated in PW/NASA rig testing was employed to reduce tip speed for reduced noise and increased efficiency using advanced rotor shroud casing treatment (TS30) and advanced inlet technologies (ADP rig). Two additional technologies that were identified included swept fans and 3-D designed FEGV's with both having the potential for acoustic and performance benefits. Swept fans and 3-D FEGV's are discussed in the performance section of this section.

TABLE IV. - CURRENT TECHNOLOGY AND ADVANCED TECHNOLOGY FAN PARAMETERS

| | Current Technology | | Advanced Technology |
|---|---|---|---|
| PR Stage Cruise/T/O | 1.35/1.41 | | 1.36/1.41 |
| Rotor Tip Diameter (H/T) | 140"(0.40) | | 143.1" (0.39) |
| Aspect Ratio Tip/Root | 1.46/3.32 | | 1.46/3.32 |
| No. of Blades | 16 | | 16 |
| W/A - Cruise | 42.5 | | 42.5 |
| - T/O | 41.7 | | 41.6 |
| Utip - Cruise | 1190 ft/sec | | 862 |
| - T/O | 1290 | —25% → | 965 |
| Efficiency - Cruise | Constrained Base | | +3.0% |
| - T/O | Constrained Base | | +3.0% -2.1% SFC |
| (pitch) | (-6.3°) | | (-6.3°) |

A technology that will allow the fan to run at lower tip speeds is advanced fan case tip treatment. A version of this treatment was demonstrated in first generation technology testing and allowed the fan to operate at higher aerodynamic loadings with greater inlet distortion tolerance. A test data summary is shown in Figure 5. This higher loading technology would allow the fan tip speed to be reduced from the baseline level of 1290 ft/sec. at takeoff to 1055 ft/sec. as shown in Figure 6.

Another technology that directly impacts tip speed is reduced inlet distortion which would also require less base surge margin and a lower fan tip speed. Reducing the inlet distortion to a separation free condition over the full required angle of attack range will allow takeoff tip speed to be reduced further to 955 ft/sec. A summary of the distortion/tip speed relationship is shown in Figure 6.

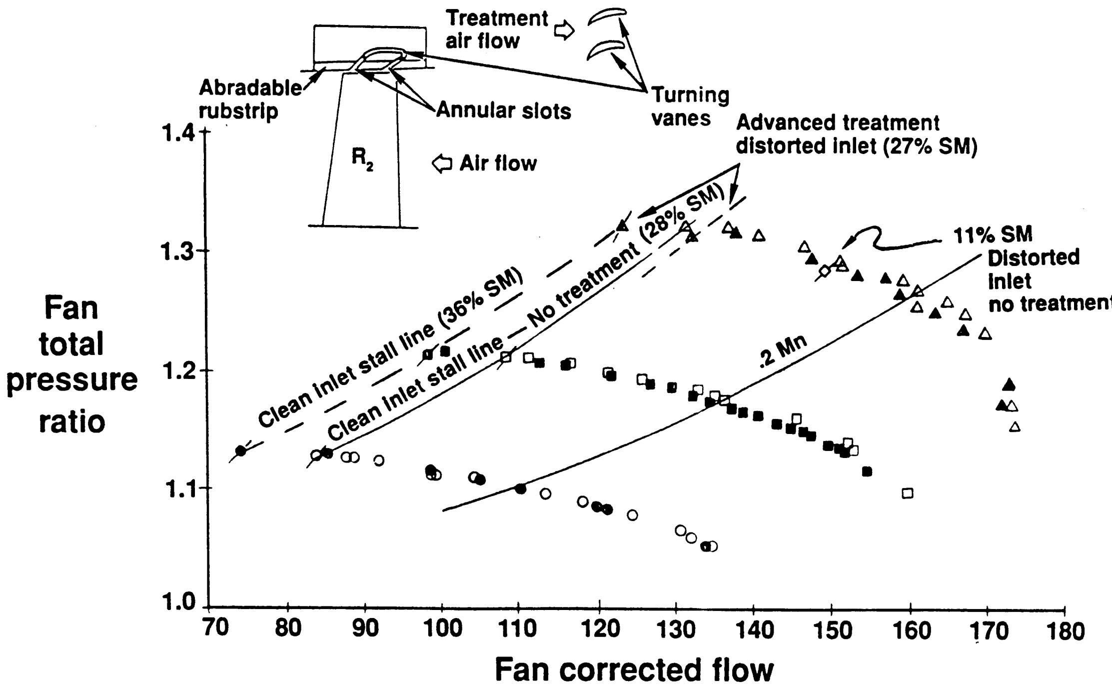



Figure 5.- Advanced Rubstrip Treatment Testing Showing 16% Increased Surge Margin in the TS-30 Technology Rig Was Employed to Reduce Tip Speed in the Second Generation ADP Study.

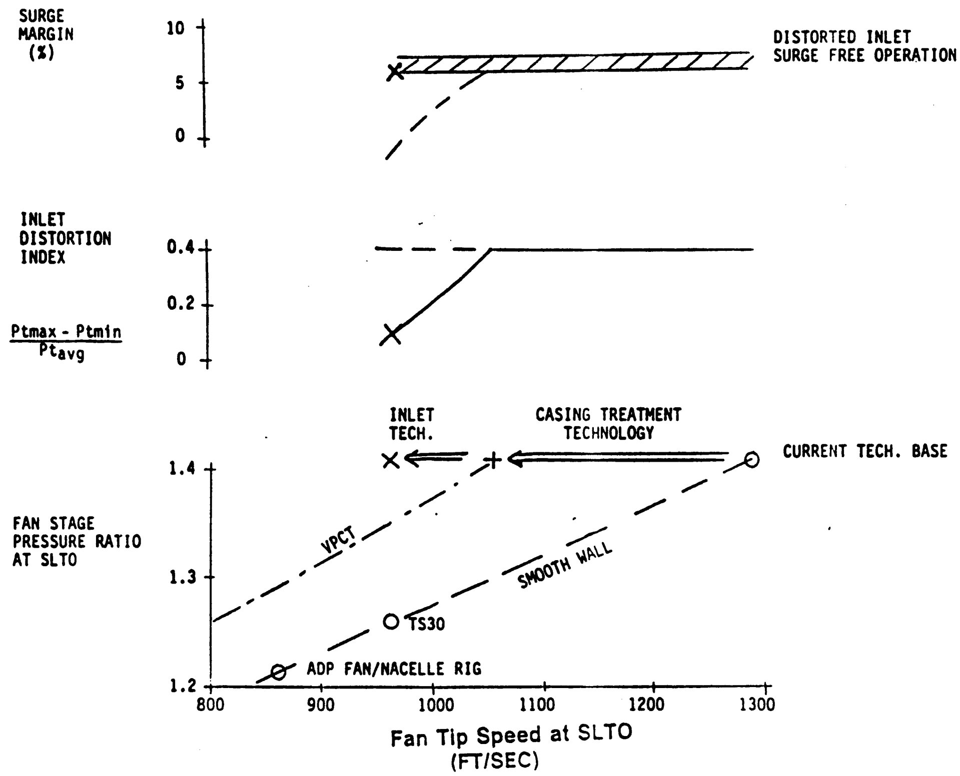
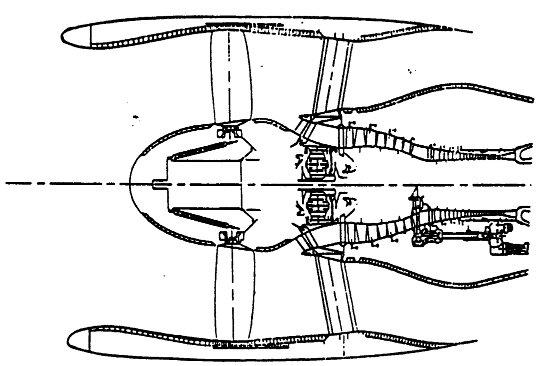



Figure 6.- Takeoff Tip Speed of the Second Generation ADP is Reduced While Holding Surge Free Operability Margin Using Advanced Rotor and Inlet Technologies.

Additional geometric changes were considered to reduce fan tip speed and acoustic noise levels such as 1) tighter airfoil gap/chord ratio (higher solidity), 2) additional flowpath convergence, 3) a higher specific flow via a tip diameter reduction, and 4) blade pitch change magnitudes between cruise and takeoff. Changes in the first three above design parameters were rejected due to adverse trades in other areas. Tighter gap/chord ratio raised the blade weight or airfoil count and aggravated either the airfoil torsional frequency concerns or increased pitch mechanism difficulty. Tip flowpath convergence had negative impacts on blade performance and stability margin with required looser clearances to allow for blade pitch changes. A small increase in inlet specific flow quickly raises inlet Mach number with an adverse impact on performance and acoustics. Variations in fan blade stagger were used to provide the minimum cruise tip speed for a required SLTO tip speed to take full advantage of the variable pitch capability of the fan. The resultant blade angle at takeoff is -6.3° stagger from the cruise setting to provide required takeoff tip speed without adversely affecting performance or acoustics.

Figure 7 gives a geometric and aerodynamic comparison for the fan and FEGV between our test rig experience and proposed technology vehicle.



DESIGN FEATURES:
- 16 Fan Blades
- 34 Fan Exit Guide Vanes
- 1.8 Spacing/Fan Blade Chord

| | FAN | | | EGV | | |
|---|---|---|---|---|---|---|
| | 17" Rig | TS30 | 2nd GEN | 17" Rig | TS30 | 2nd GEN |
| **Geometry** | | | | | | |
| No. Airfoils | 16 | 18 | 16 | 40 | 24 | 34 |
| Hub/Tip Ratio | .443 | .426 | .390 | | | |
| $\tau$/b root | .600 | .660 | .660 | .390 | .470 | .470 |
| tip | .960 | .960 | .960 | .910 | .930 | .930 |
| AR root | 1.82 | 2.40 | 2.45 | | | |
| mean | | | | 3.00 | 1.60 | 2.55 |
| tip | 1.33 | 1.54 | 1.45 | | | |
| t/b root | .099 | .099 | .099 | | | |
| mean | | | | .082 | .085 | .085 |
| tip | .020 | .020 | .022 | | | |
| **Aero at Cruise** | | | | | | |
| Pr duct stage | 1.21 | 1.294 | 1.360 | | | |
| Wc/A le | 40.8 | 42.6 | 42.5 | 35.5 | 34.0 | 33.8 |
| Utip | 802 | 953 | 862 | | | |
| M1 rel tip | .940 | 1.09 | 1.00 | | | |
| $\alpha^*$in | | | | 60.6 | 58.4 | 51.5 |
| Mn in | | | | .626 | .590 | .689 |
| Df avg | .391 | .434 | .524 | .190 | .172 | .336 |

Figure 7.- The TS30 and 17" ADP Rig technologies Relate Well to the Second Generation ADP Due to Their Design Similarities.

## Airfoil Geometry

A preliminary pass at defining fan and FEGV airfoil shape was conducted when a fan tip speed was determined. Given the level of gap/chord ratio, thickness/chord ratio, radial work distribution, section axial work distributions, and airfoil incidence and deviation levels from first generation experience and this study, an airfoil surface coordinate file was produced for structural analysis and weight estimates. The blade pitch setting identified in fan/nacelle rig testing for required reverse thrust caused blade or contact interference in the blade root area. To allow full reverse pitch capability, a trailing edge root chord cutback was included in the blade coordinate definition. The straight airfoil is shown in Figure 8.

A similar airfoil definition process was executed to produce an FEGV coordinate file. As shown in Figure 9, the airfoil was tilted rearward 10° to provide the shortest nacelle possible while maintaining fan to FEGV spacing at mid-span to 1.8 times fan axial chord.

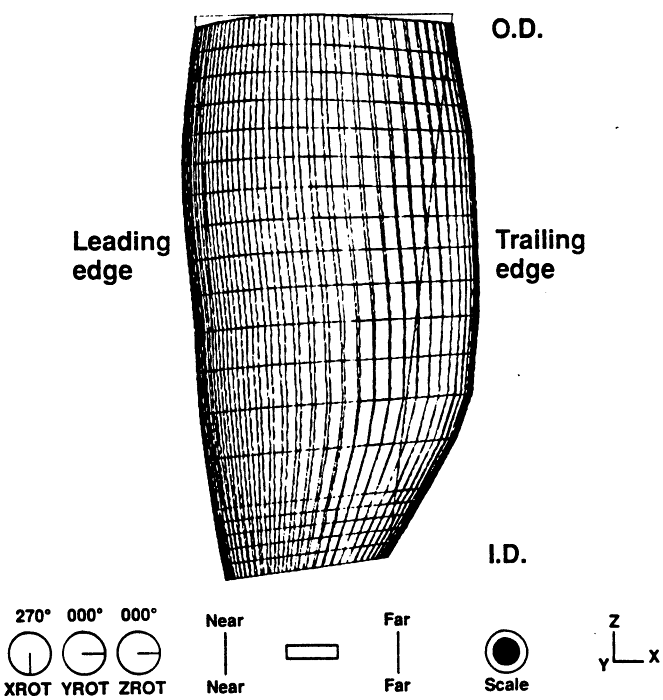



Figure 8.- Straight Fan Blade. Side view with root cutback

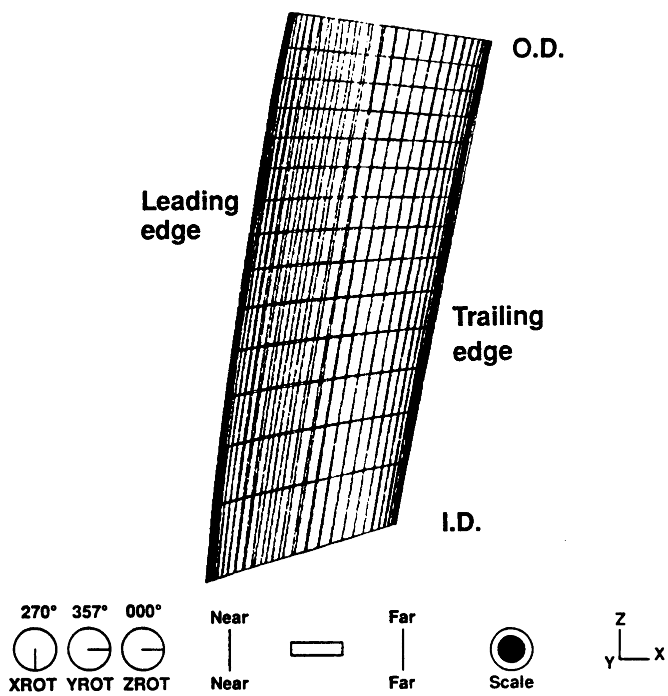



Figure 9.- FEGV Side View. 10° rearward stack

## Performance Potential

Relative to the baseline current technology fan, the reduced tip speed resulted in a 3.0% efficiency improvement for the fan at the inlet to the duct. This improvement resulted from a lower fan Mach number, even with higher blade loadings.

As a result of the lower tip speed at constant pressure ratio with advanced technology, the Mach number, swirl angle and loadings on the FEGV increased. The increased loadings on the FEGV also increased the pressure loss and reduced the efficiency gains produced in the fan. The 3.0% gain in fan only efficiency was reduced to a 1.6% stage efficiency gain.

As mentioned earlier, two additional technologies that were identified as having potential for both aerodynamic performance and acoustic benefits are swept fans and 3-D designed FEGV's. Projected benefit of these technologies is the potential to increase the stage efficiency improvement to 3.0% or greater.

Swept Fans

Preliminary definition of swept fan geometries were created based on estimates of leading edge normal Mach number and simple beam analysis for stress levels. The airfoil sections were stacked to provide a leading edge normal Mach number of 0.8. The airfoils were also stacked axially in an 'arrow' shape to minimize root stresses and stacked tangentially to limit minimum axis bending stresses. The resultant compound sweep angle in both the axial and tangential direction was 36.5° at the tip.

A side view of the forward and aft swept fans are shown in Figures 10 and 11. Figure 12 shows the straight, forward swept, and aft swept fan in the design flowpath with their respective spherical shroud shapes. Because a primary goal of swept fans is to also reduce acoustic noise, both a forward and an aft swept fan were considered. While both are theoretically identical for shock loss reduction, the acoustic benefits due to axial spacing and secondary flow may be considerably different. Without an analysis of the 3-D flow field and magnitude of surface shock reduction, no absolute performance benefit can be made.

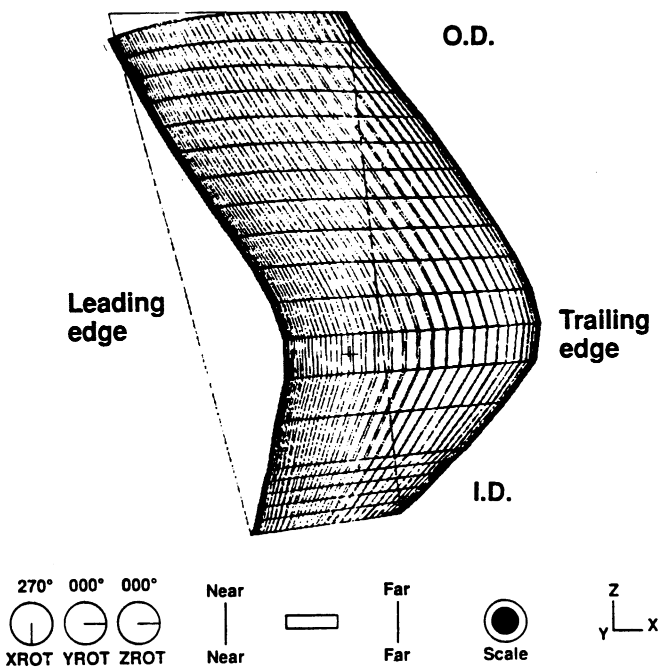



Figure 10.- Forward Swept Fan Blade Side View.

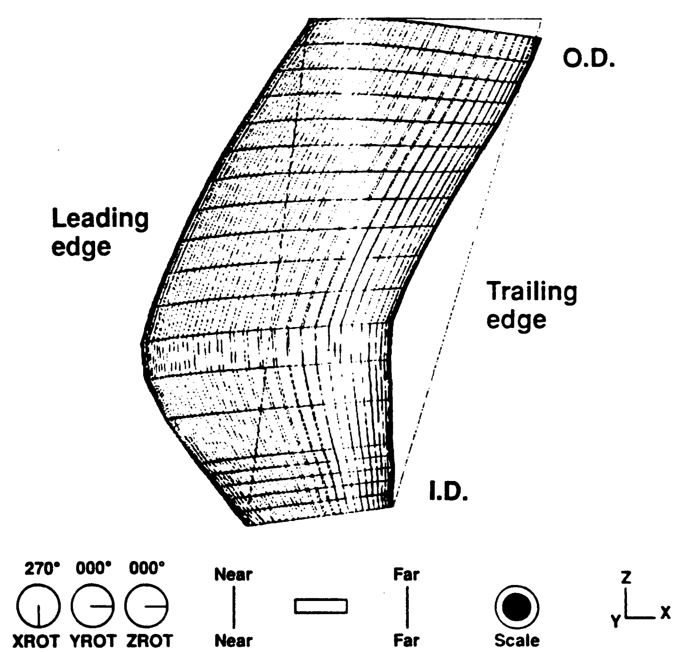



Figure 11.- Rearward Swept Fan Blade. Side View.

**Approach**
- **Leading edge swept to 0.8 normal Mach number (20% reduction at tip)**
- **"Arrow" shape employed to minimize blading stress**

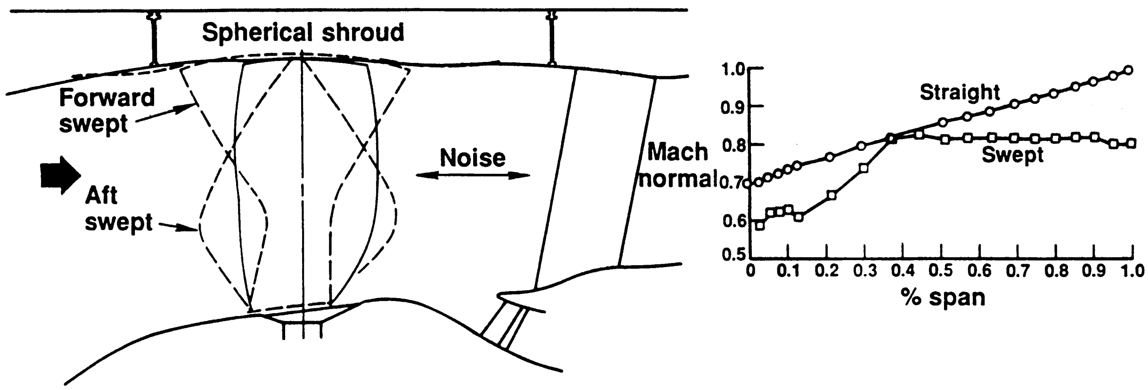



Figure 12.- 3D Swept Rotor Technology. The feasibility and potential benefits of forward and aft swept blades were assessed in preliminary designs.

3-D Fan Exit Guide Vane

As indicated previously, the higher FEGV loading for a low speed fan resulted in a 1.4% penalty in potential stage efficiency. From experience with multistage PWA 3-D designed (Bowed) stators, the stator loading can be redistributed for performance benefit. Figures 13 and 14 summarize the FEGV loading, Mach number and potential pressure loss reduction based on PWA experience. Potential benefits of the 3-D design would allow the base level of pressure loss to be maintained at the higher loadings, eliminate the 1.4% stage efficiency penalty and restore the full 3.0% potential stage efficiency improvement for a second generation ADP engine. The straight FEGV airfoil sections were stacked to reflect a first pass estimate of required airfoil shape to realize the aerodynamic benefit. Figure 15 presents a rear view of the straight and bowed FEGV for comparison. Because the FEGV cutting through rotor wakes is a significant duct noise source, the final shape of the FEGV would include acoustical input based on computational codes to provide an acoustical benefit as well (refer to Acoustics section).

An estimate of the bowed airfoil stiffness relative to a straight FEGV indicatedthat the mechanical design of a bowed structural FEGV will also require significant structural analysis (refer to Mechanical Design/Structures section).

## Approach

- Axial sweep to increase acoustic spacing from rotor
- Bowed 3D design based on P&W multistage experience to reduce wall losses aggravated by higher loading and Mach No.

## Benefits

- Reduced noise resulting from increased spacing to rotor and wake cancellation concepts
- Total pressure loss reduction equal to 1.4% in stage efficiency neutralizing the effects of the increased loading and Mach No.

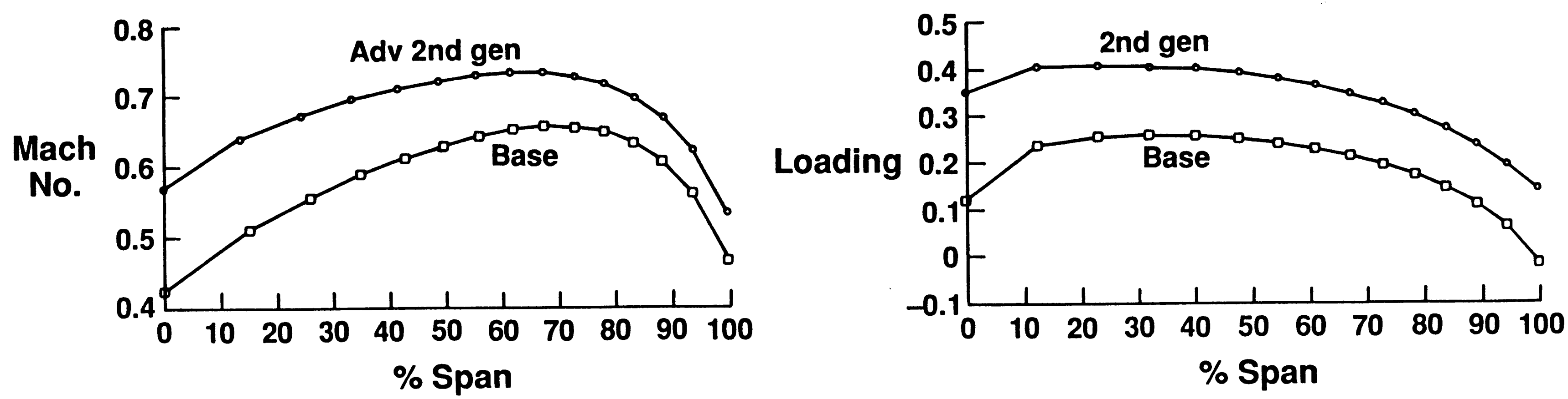
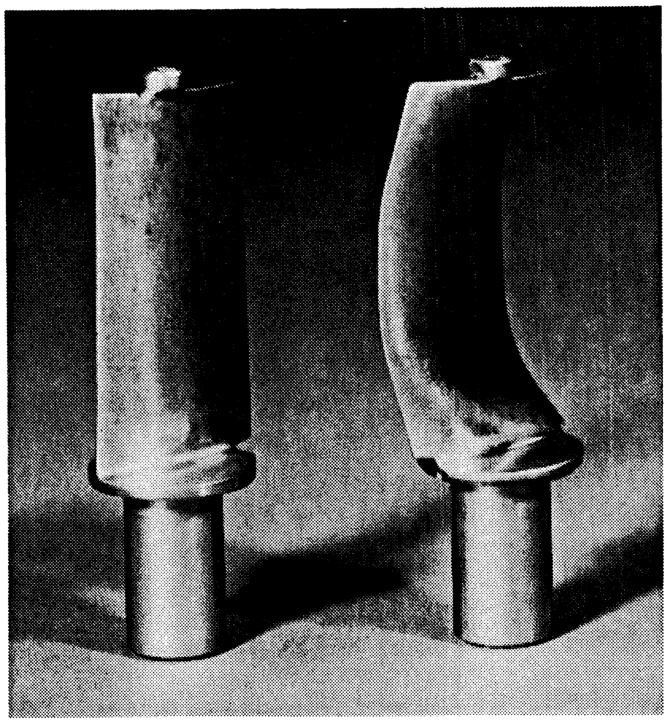



Figure 13.- 3-D FEGV Design Study.

## P&W Bowed Stator Program

**Bowed last stator improved 3 stage rig efficiency 3/4 percent equivalent to 0.5% $\frac{\Delta Po}{Po}$ in last stator**



Conventional Stator    Bowed Stator

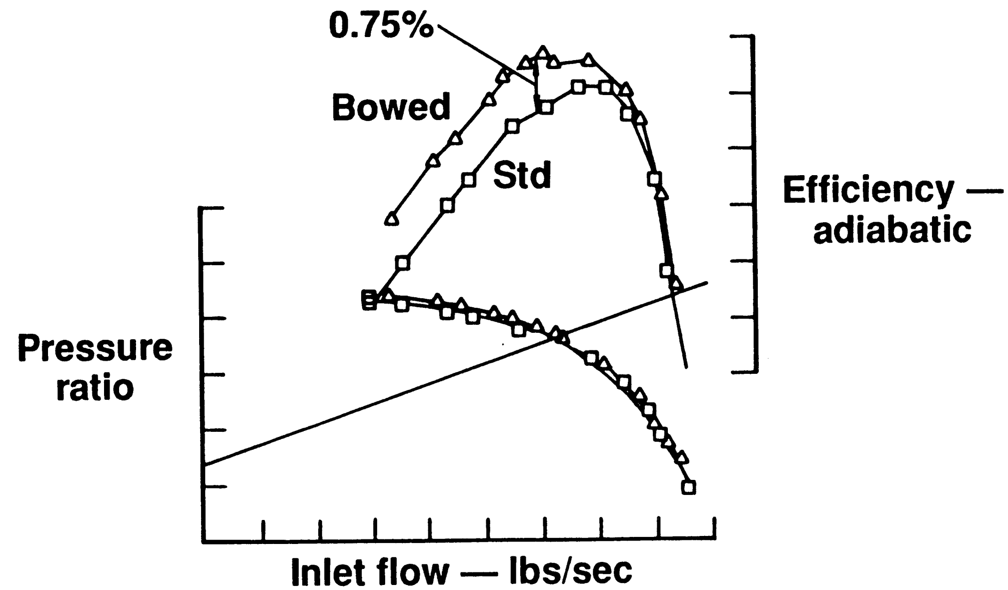



Figure 14.- Methods of Improving Compressor Stator Performance Developed at P&W Using 3-D Computational Fluid Dynamics can be Employed to Reduce Second Generation FFEGV Loss.

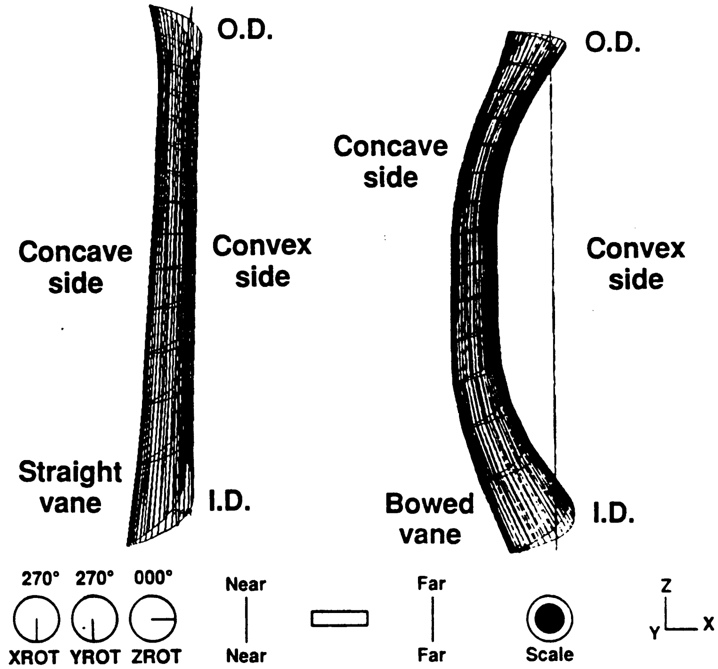



Figure 15.- Straight and Bowed Fan Exit Guide Vane - Rear View.

Torsional Frequency Study

After the coordinate file for the straight fan was produced, a structural analysis was conducted for a solid titanium blade. The first mode torsion frequency was lower than the first generation ADP fan experience. The low first torsion frequency crossed the three times rotor speed (3E) frequency in the operating range. Having a blade first torsion 3E resonance in the operating range is beyond our P&W's experience and was expected to produce high resonance stress. The low first torsion frequency also lowered the torsion flutter parameter to below our experience. A first generation ADP fan had torsion flutter outside the operating range. A lower torsion flutter parameter would move the flutter near or into the operating range. The 3E torsion resonance in the operating range and torsion flutter at or near the operating range would limit the proposed test program. Since the purpose of this study was to define the technologies necessary to produce a low noise fan, any identified restriction that would impact or limit the proposed test program is needed to be investigated.

The following geometric changes were considered to change the blade torsional frequency:

- Radial work distribution - camber
- Radial thickness distribution - t/b
- Number of airfoils - aspect ratio
- Root solidity
- Fan hub/tip ratio
- Axial location of maxiumum thickness
- Amount of root cutback for reverse

Due to the limited scope of this study, no final solid titanium blade was defined that would solve the torsional frequency problems. A solid titanium blade offers the benefits of tight surface contour tolerance control and easy recamber capability for a development program. Preliminary analysis suggests that a composite material airfoil would satisfy torsional frequency and stall flutter requirements and represents an alternative blade that should be pursued as a technology item. Details on the torsional frequency study are presented in the "Mechanical Design/Structures" of this report.

## Test Program

Three fan aero advanced technologies were identified that will contribute toward a reduced fan tip speed, a reduced noise level, and improve performance of a second generation ADP engine. These technologies are advanced casing treatment, swept rotors, and 3-D FEGV's. Advanced inlet designs to provide reduced inlet distortion are discussed in the Nacelle Aero section.

### Advanced Casing Treatment

The suggested test program for advanced casing treatment will develop a fan case tip treatment that will allow stable operation of the fan at low tip speed with acceptable levels of stress when subjected to expected levels of inlet distortion. The test program will determine whether VPCT enables the higher camber lower tip speed designs to sustain the loading levels demonstrated in the TS30 rig tests. The development process will combine the design of the highly loaded advanced fan and test data from first generation advanced casing treatment to design improved casing treatments. A summary of this development process is shown in Figure 16. Questions also need to be answered on how the VPCT benefit changes with fan tip clearance for straight, forward and aft swept blades, and ultimately on how effective the treatment is in reverse flow operation.

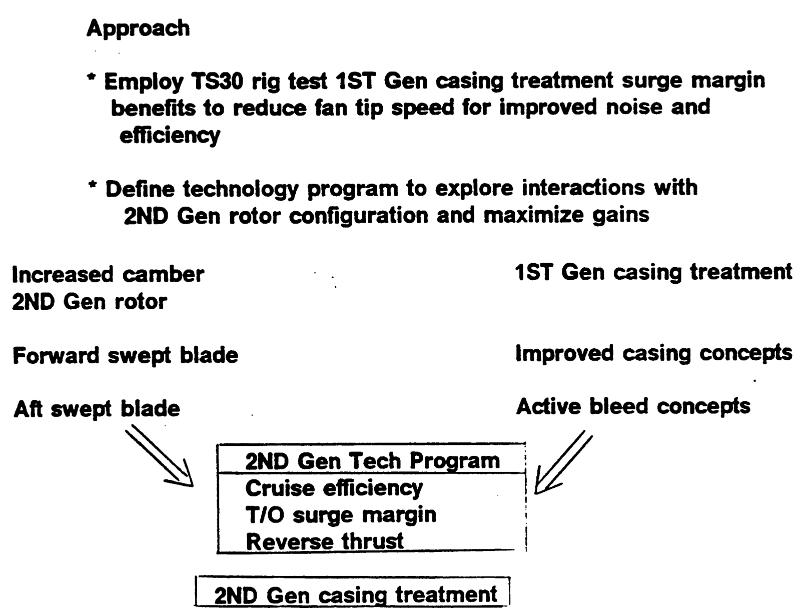



Figure 16.- Fan Casing Treatment Study

## Swept Fans

The suggested test program objective for swept fans will be to conduct a multiple build rig development program to determine the aerodynamic benefit of swept fans at low tip speeds for a radially matched fan and to determine any operability implications of sweep. A development program will be needed to produce a final swept fan that is efficient, provides a true indication of the acoustic benefits of sweep, and is not improperly matched radially with large wakes. A 3-D swept fan design concept has the potential of increased efficiency and reduced noise by reducing airfoil surface Mach number and diminishing blade wakes. The objectives of a swept fan development program are to:

- develop swept blade aerodynamics and operability in a significantly different radial flowfield.
- quantify and rank efficiency and noise benefits.
- assess sensitivity to tip clearance and axial spacing.
- assess interaction with casing treatment options.
- define reverse thrust characteristics.

A full 3-Dimensional analysis was not possible during the 3-month study and the actual potential of either performance or acoustic benefit could not be determined. To gain information to allow proper 3-D modeling of the flow field, LDV data to define velocity vectors would be required during testing.

## 3-D Fan Exit Guide Vane

The goal of the suggested test program for FEGV's will be to produce an efficient, structural FEGV that provides acoustic benefits. Due to the complexity of the airfoil shape, a 3-D design needs to be executed. Shaping the airfoil for noise wave cancellation will be explored and a bowed FEGV that is structural and capable of carrying nacelle loads while maintaining reasonable fan tip clearances will be required.

Table V lists the three technologies, the projected benefits previously discussed and the program objectives in evaluating these technologies.

TABLE V. - PROJECTED BENEFITS OF TECHNOLOGY PROGRAMS

| Technology | Projected Benefits | Technology Program Objectives |
|---|---|---|
| 1. Advanced casing treatment | o Increased surge loading<br>o -25% tip speed<br>o +3% efficiency<br>o Reduced noise | o Assess stall margin with 2nd generation geometry.<br>o Assess reverse thrust potential<br>o Verify efficiency gain<br>o Verify noise reduction<br>o Optimize casing treatment configuration |
| 2. Swept Rotor | o Increased efficiency<br>o Reduced noise | o Develop acceptable full span aero<br>o Optimize rotor/casing treatment combination for max efficiency benefit with acceptable operability and structural characteristics<br>o Assess tip clearance effects<br>o Assess reverse thrust potential |
| 3. 3-D Bowed/Swept FFEGV | o 1.4% stage efficiency<br>o Reduced noise | o Assess efficiency benefit with structurally acceptable design<br>o Determine effect of pylon match |

### Test Vehicles

In order to develop the outlined technologies, the fan aero test program can be divided into three types of testing;

- fan and FEGV performance/efficiency
- fan stability margin
- reverse thrust capability

Table VI presents the test variables and vehicle requirements needed to achieve the test program objectives and identifies the fan/nacelle interaction rig and a fan performance rig that will be needed to meet those requirements.

Using the test variables provided in Table VI, two rigs were identified to meet the requirements as discussed in the following subsections.

#### Fan Performance Rig

This rig will be used to measure absolute levels of fan and FEGV performance, develop swept fan aerodynamics and determine performance and stability changes with variations in advanced tip casing treatment and clearance.

#### Fan/Nacelle Interaction Rig

This rig will be used to determine fan operability with the nacelle at angle of attack and to determine reverse flow thrust levels, fan starting capability and levels of core inlet distortion. Acoustic testing will also be a significant portion of the interaction rig program. The fan/nacelle rig will include fan operability hardware with a bellmouth to measure flow, an inlet distortion screen rotator to allow distortion testing, and a downstream diffuser to vary back pressure and allow fan flow mapping, stability line definition and flutter boundary mapping.

Figure 17 shows a summary of testing to be conducted in each rig with the flow of data resulting in a second build of the fan/nacelle interaction rig with hardware defined from development in the fan performance rig.

### Tasks and Schedule

A program schedule was created based on the technologies to be developed, types of testing required, and the two test vehicles to be used. The information gained from the fan performance rig development testing will be used in a build of the fan/nacelle interaction rig where the best technologies and hardware will be combined for confirmation testing. A multiple build/test of the fan performance rig will be required to modify airfoil shapes and advanced casing design parameters in order to develop high performance for a swept fan with advanced casing treatment and a 3-D FEGV.

## TABLE VI. - FAN AERO TEST VARIABLES AND VEHICLE REQUIREMENTS

### FAN AND FEGV PERFORMANCE

Test variables:

a) Evaluate performance of straight and swept fans with changes in Reynolds number, tip clearance, tip treatment and blade stagger.
b) Evaluate performance benefits of a 3-D designed FEGV.
c) Three builds of a swept fan are required to obtain the correct radial match of passage aerodynamics to produce maximum performance improvement and valid acoustic comparisons.

Test vehicle requirements

a) Map fan and FEGV performance at various speeds, pressure ratios and inlet pressures.
b) Accurately measure exit radial temperature to identify radial benefit of clearance and tip treatment.
c) Measure and record temperatures to ±0.1° accuracy for absolute efficiency calculation.
d) Define internal flow field with LDV survey.
e) Document FEGV loadings with surface static pressures.

### FAN STABILITY MARGIN

Test variables

a) Measure clean inlet surge margin of fans.
b) Measure surge margin with changes in inlet distortion.
c) Determine effect on stability of changes in VPCT design.
d) Determine effect on stability of changes in tip clearance.

Test vehicle requirements

Test in a compressor rig with capability to:

a) Vary back pressure to stall fans and map flutter boundary.
b) Record high speed transient data to define stall boundary.
c) Test with distortion screens representing nacelle inlet distortion patterns to repeatablly quantify stability margin with geometry changes.
d) Verify operability with equivalent hardware in a fan/nacelle interaction rig.

### REVERSE THRUST CAPABILITY

Test variables

a) Determine effect of blade stagger on thrust and fan stall.
b) Determine effect of VPCT on fan stall.
c) Vary geometry to minimize core inlet pressure distortion.

Test vehicle requirements

Test in a fan/nacelle interaction rig with capability to:

a) Measure level of reverse thrust.
b) Vary tunnel speed.
c) Record high speed transient data to define fan stall.

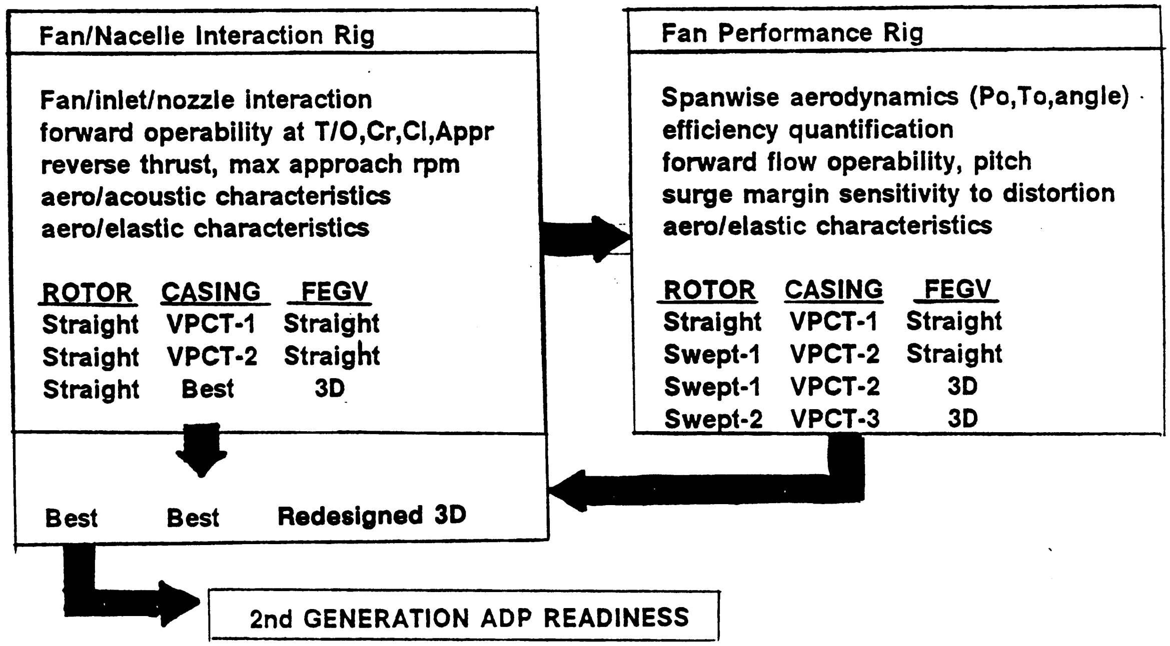



Figure 17.- Performance Potential, Stability Margin and Reverse Thrust Capability of the Second Generation ADP Fan are Developed by Evaluating Design Concepts in the Fan/Nacelle Interaction and Fan Performance Rigs.

The Advanced ADP technology program will require tasks related to aerodynamic design, fan performance rig testing and fan/nacelle interaction rig as shown in Figure 18. The arrows indicate where hardware or design information crosses from one task to another and coordinates the inputs from other technologies into a build of the interaction rig. The results of the development process in the fan performance rig will be incorporated into the second build of the interaction rig to verify swept fan aerodynamics, along with hardware from development programs in other areas, for final acoustic assessment.

The program tasks that are shown in Figure 18 are described below.

### Aerodynamic Design

This task consists of work to be performed as shown below:

| Task Description | Period of Performance |
|---|---|
| Straight fan, FEGV's, Flowpath | 9 months |
| Swept Fans | 6 months |
| Redesign as required | 6 months |

The straight fan, FEGV's, flowpath task will include design coordination between the respective disciplines to provide a flowpath with acceptable airfoil spacing, structural integrity, and mechanical feasibility that will fit within nacelle dimensions. Specifications would also be created for instrumentation, distortion screens, and fan operability equipment. The flowpath configuration and airfoil geometry would be based on the study just completed.

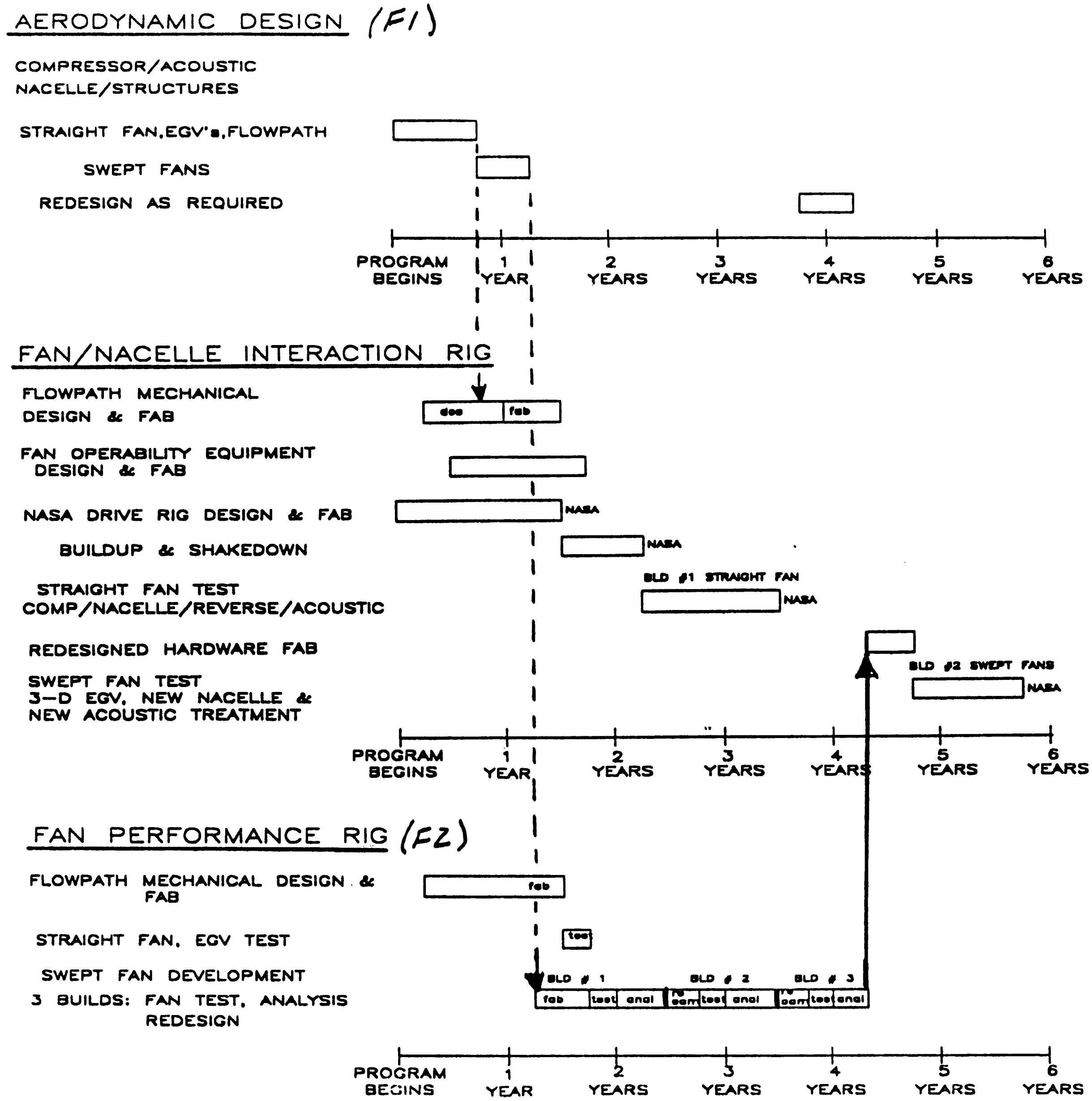



Figure 18.- Fan Aero Technology Program Schedule. The fan aero technology program formulated for the second generation ADP integrates advanced concept evaluation in fan/nacelle interaction and fan performance rigs to provide technologies readiness in six years.

Currently, a limited data base exists for swept fan design. Under the swept fan task, a 3-D computational code will be used to determine the geometric shape required to realize the benefits of sweep.

Redesign will be performed as testing proceeds during build one of the fan/nacelle interaction rig. During this effort, areas for aerodynamic improvement may be discovered and aerodynamic factors may also have to be changed for nacelle, structural, or acoustic considerations. Some areas may include modifications in tip casing treatment, flowpath changes for reverse flow operability or core inlet distortion or flowpath/airfoil changes for acoustic tone cutoff benefit.

Fan/Nacelle Interaction Rig

During each build of the rig, testing will include a fan operability check with distortion screens, fan mapping for flow and flutter boundary, nacelle angle of attack for inlet distortion, reverse flow and fan starting capability, and acoustic measurements.

Flowpath mechanical hardware and fan operability equipment definition will be provided from the aerodynamic design effort. Build 2 of the rig will include redesigned hardware and flowpath changes will be defined during the aerodynamic redesign, and airfoil changes such as a swept fan will be defined from the fan performance rig program.

Fan Performance Rig

The work to be performed under this task and period of performance are shown below:

| Task Description | Time (months) |
|---|---|
| Flowpath mechanical design and fabrication | 15 |
| Straight fan, FEGV test | 3 |
| Swept fan development | |
| Performance testing of forward and aft sweep | 9 |
| Stability testing of swept fans | |
| Three Builds; blade fabrication, test, analysis and redesign | |

Hardware to be fabricated under the first task item will include a straight fan blade set, straight and 3-D FEGV sets, 3 sets of forward and aft swept fan blades, cases, instrumentation, distortion screens, sets of base and advanced fan tip casing treatments. Peformance mapping at various blade staggers, tip clearances, and fan case tip treatments will be conducted under the second task item. At the same time, FEGV data will be obtained. Under the third task item, three performance/stability builds of swept fan geometry will be required for both an aft and/or forward sweep before acoustic testing is conducted.

## CONCLUSIONS

Aero Design

1. A current technology fan rotor configuration produced for a large thrust over water twin aircraft will require a 25% increase in tip speed, resulting in 1.5% lower efficiency and increased noise due to the constrained diameter cycle.

2. Advanced rotor casing treatment and inlet distortion technologies developed in 17" ADP and TS30 rig testing can reduce tip speed by 25% in the constrained diameter cycle with a projected 3% improvement in efficiency (2.1% SFC) and significantly reduced noise.

3. Forward and aft swept rotor technologies have the potential for additional efficiency improvement and noise reduction but require technology program testing for development quantification and ranking.

4. The fan stage efficiency benefit of advanced casing treatment will be reduced from 3.0% to 1.6% due to increased Mach no. and loading of a current technology FFEGV.

5. 3D bowed/swept FFEGV technology based on P&W multistage rig testing has the potential to restore the stage efficiency benefit to 3.0% while providing further noise reduction.

Test Program

In order to effectively develop technologies identified during the NASA Low Noise Study, a test/development program is needed to:

1. Measure performance potential for advanced ADP fans and FEGV's.

2. Develop swept blade aerodynamics and operability.

3. Evaluate stability margin at reduced tip speeds with advanced fan case treatment.

4. Verify reverse flow/thrust capability.

## MECHANICAL DESIGN/STRUCTURES

### Candidate Selection

Preliminary ADP fan rotor configurations were evaluated for the baseline ADP constrained diameter design with current state-of-the-art technology and for several options of the ADP engine employing advanced technology concepts to reduce noise.

#### Fan Blade

Several unswept fan configurations of the ADP fan rotor for the 862 ft/sec. cruise tip speed were selected for structural and mechanical design analysis. Several designs were evaluated to resolve a baseline design, first torsion resonance problem, in the operating range. Attempts at moving this resonance out of the operating range included increasing the root thickness and tip thickness.

A mechanical design review of the straight blade was conducted which included scaling the VPCT concept to the constrained fan size of 143" which was then incorporated into the nacelle design. Review of the straight blade also verified the amount of blade turning to the clash point in full reverse. For the straight blade, this limit was 95° from the cruise position. This limit is also the maximum reverse position. When turned 95°, the incidence angle at the tip is the same as the ADP demonstration engine at full reverse despite the lower angle of pitch change turn (95° vs 107°). This indicates that the design of the low noise fan rotor is capable of obtaining full reverse thrust capability. There were no problems in the normal forward thrust operating position.

A review similar to the straight blade was conducted on a second blade with an aft swept tip. This review indicated the aft swept tip blade design was also capable of full forward and reverse thrust operation.

Vaned Passage Casing Treatment (VPCT) Containment

In order to achieve the low fan tip speeds required to significantly impact noise generation, increased fan stall margin is required. The vaned passage casing treatment concept has shown a substantial increase in stall margin in rig and engine testing. An existing VPCT design was scaled up to the 143-inch fan size for this study.

Construction of the VPCT relied heavily on the use of composites and honeycomb to minimize the weight impact on a large engine. The VPCT was incorporated into an integral case and nacelle concept. The engine fan case and outer walls of the nacelle are tied together at bulkheads to form a box section for increased stiffness of the structure.

The fan rubstrip length was sized to accommodate rubbing in any fan running position. Although containment is not directly related to fan noise generation, the VPCT is critical to the design. The amount of room taken up in the nacelle by the VPCT package could impact the viability of a Kevlar containment system. A review of the containment was not included and appears feasible. However, the nacelle contours may have to be modified to allow space for the Kevlar to move and absorb energy if there is a blade loss. Additional analysis and testing are required to determine the required radial clearance. The clearance will also depend on the blade material and construction.

The containment is made up of layered Kevlar belts wrapped around the outside of the VPCT area. The number of layers was determined from current P&W criteria, based on blade energy. Expansion of the Kevlar is limited to 3" before hitting the outer nacelle wall. The Kevlar axial lengths were sized to current P&W criteria and FAA advisiories to prevent particles that move axially when leaving the engine.

The use of bowed FEGV's to further reduce noise was also investigated. It was shown that the stiffness of bowed vanes was one-tenth that of straight vanes. Their use as structural members to support the fan case and nacelle as currently designed is unlikely. The engine would probably be redesigned with FFEGV's providing aerodynamic turning and an additional structural case behind these vanes to provide support for the outer case and nacelle.

Weight, Manufacturing Cost and Maintenance Cost

Refined sophisticated analytical techniques and computer programs were used to evaluate the propulsion system weight, cost and maintenance cost. Pratt & Whitney has compiled an extensive data base on current engines, including commercial engines such as the PW4000, PW2000, and V2500 as well as data on military engines such as the F100 and YF119.

Performance data in the form of preliminary flowpath staging, airfoil quantities and dimensional requirements as well as component temperatures, pressures and speeds were provided for use in weights, cost and maintenance cost parametric programs. After materials, configuration and manufacturing guidelines were provided, preliminary design layouts were made that illustrated unique mechanical features/configurations. A known technology base was used in parametric programs which evaluated the impact of changes in aerodynamic parameters as well as changes in configuration. These changes were then evaluated against key parts within each component affected to define the component weight/cost/maintenance cost of equivalent parts in the new engine. The guideline for the Task V, Low Noise Study Definition program is shown at the end of this section.

The primary tools that were used to evaluate engine weight were parametric programs for the major sections of the engine; inlet, fan, LPC, intermediate case, core (HPC, diffuser/burner, HPT), and LPT. Manufacturing costs were determined using the Parametric Cost Estimating program which is a computer program that contains a data base of costs and definitions for production and study engines. The data base is divided into engine modules and contains material and labor costs by engine part. Maintenace cost was evaluated using the Maintenance Cost Estimate System (MACE) program which defines an engine in terms of general engine characteristics, part lives and labor tasks. These data are combined with the cost data and typical airline maintenance labor costs for specific mission groundrules including flight length, derate, and annual aircraft use to produce parametric maintenance cost estimates. Using a known data base, the MACE program evaluated the impact of changes and compared them against key parts of other configurations. The results were then used to calculate the direct operating cost to determine the benefit of configuration changes.

The resulting weight, cost, and maintenance parameters used for the economic evaluation of the advanced technology propulsion system are +200 lbs., less than 1%, and no change, respectively. These costs are compared to an equivalent thrust current technology advanced ducted propulsion system.

## GUIDELINES FOR TASK V - LOW NOISE STUDY DEFINITION

### PROPULSON

- o Blades: 16 solid composite blades with Ni LE and TE. Attached by pinjoint to a shaft and supported in the disk by a rolling contact bearing.
- o Disk: Ti with Graphite-Epoxy reinforcing rings.
- o V/P: The variable pitch mechanism is a rotating Ti linear hydraulic system and includes the transfer bearing. High pressure is provided with an on-board rotating pump. It is made by HSD and assumes reduced markup. Links are graphite.
- o Case: Integrated with the nacelle, see nacelle for description.
- o FEC: Composite with 34 struts, ID is a torquebox, front mount is on FEC OD.
- o Front Brg: Preloaded taper roller bearings.
- o Spinner: Composite with sound treatment.

### REDUCTION GEARBOX

- o Gearbox: P&W designed and manufactured planetary fixed ring gear with 5 journal bearings. The carrier and torque shaft are titanium. Gears are advanced M50NIL material.

### INLET

- o Vanes: Titanium IGV, no A/I.
- o Case: Cast titanium case with 10 struts and no A/I, inner box and bearing support.
- o Splitter: Composite.

### LPC

- o Blade/Disk: Ti Blisks, bolted drum.
- o Vanes: All V/G except FEGV, composite vanes.
- o V/G Hrdwr: Unison rings are composite.
- o Case: Split, cast titanium.
- o Int. Case: Intermediate case is cast titanium and has 8 struts. Includes thrust attachment.
- o Bleeds: Variable bleed at intermediate case.

### CORE

- o HPC to HPT: PW4168 Growth Engine Core.

### LOW PRESSURE TURBINE

- o General: Design is 7.5 $AN^2$.
- o Trans Duct: PW4000-Type transition duct.
- o Blades: last 2 are wide chord shroudless.
- o Vanes: Solid, 3 thin vane cast clusters, PWA 1447 1st stage and PWA 655 rear stages.

LOW PRESSURE TURBINE (Continued)

- Disks: Adv. Waspaloy disks with separate rotating seals. Disks are bolted.
- Cases: INCO 718 case.
- ACC: External steel tubes; 2 sets.
- Low Shaft: Advanced Waspaloy
- TEC: Fabricated titanium with mount rig.

BEARINGS

- Bearings: PW4000 design with carbon seals.
- Supports: Supports are all titanium.
- Shafts: Front rotating stubs and shafts are titanium.

CONTROLS/ACCESSORIES

- General: PW4000-type hardware where applicable
- Gearbox: Full duty/core mounted main gearbox (A1 housing), with an angle gearbox.
- Fuel Ctrl: New electronic fuel control with mechanical metering unit; includes V/P controller.
- Oil Tanks: Gas generator and reduction gearbox each have a steel oil tank and oil cooler.
- V/G Act.: The LPC V/G is actuated by 3 hydraulic motors, the HPC V/G by a hydraulic piston. The LPC has no bell crank.
- V/P: V/P control unit.

NACELLE/EBU

- General: Rohr design, short duct, composite, Dynarohr sound treatment.
- Fan Cowl: Ti honeycomb/composite facing/Kevlar containment, forward containment, no reverser. 2.5" forward and 2.5" rear honeycomb thickness including fan nozzle. There is an "A" flange forward of the Kevlar. Cowl is split axially for transportability. The fan case wall has vane passage case treatment (VPCT).
- Core Cowl: 2.0" thick Ti core with composite facing.
- Other: Included in the EBU is a supplemental cooling system with ACOC, valves, and nacelle integrated cooling duct. The ACOC is in the bifurcation.

POWERPLANT MOUNTS

- General: FEC/TEC, 2 plane mounted, with thrust links to the intermediate case.

## FAN STRUCTURAL ANALYSIS

### Introduction

Several noise ADP fan designs were evaluated to determine if any inherent problems existed with the candidate geometries. All of the geometries were examined in the engine size with scaled TS-30 rig attachment flexibilities. Initially, all of the technical drawings were analyzed in solid titanium. Although low bending and torsional frequencies created tuning and stall flutter concerns, the use of composite construction methods were able to remedy both areas of concern.

Generally, ADP fans are getting larger due to higher thrust and lower noise requirements (Table VII), resulting in lower natural frequencies. Figures 19 and 20 show the first generation ADP fan resonance experience in the low noise ADP tip diameter. Torsional frequencies drop as the aerodynamic technology advances, taper and aspect ratios are increasing while hub/tip ratios are decreasing, blades are also getting heavier and designing a lightweight retention system is becoming more difficult. Therefore, lighter weight blade construction methods are needed.

TABLE VII.- GEOMETRY COMPARISON OF ADP FAN BLADES

| Parameter | Advanced Turbofan | ADP Nacelle* | TS-30 | Low Noise ADP |
|---|---|---|---|---|
| Solid Ti Weight $lb_f$ | 53 | 143 | 82 | 106 |
| Aspect Ratio | 2.23 | 1.82 | 2.40 | 2.45 |
| Hub/Tip Ratio | 0.316 | 0.443 | 0.426 | 0.390 |
| Taper Ratio (no TC cutback) | 1.44 | 1.35 | 1.56 | 1.68 |

*in Low Noise ADP size

### Blade Modeling and Analysis Techniques

All designs were modeled in a 143.1" fan tip diameter engine size. To analyze these designs for rig installation, the TS-30 fan attachment flexibilities were scaled to the engine size. The analytical results, such as frequencies and stresses, are scalable to other tip diameters provided the same airfoil shape is preserved. Finite element analysis were performed using PSTAEBL, P&W's airfoil structural optimizer. This is a revised STAEBL developed under a previous contract. A NASTRAN steady stress and vibratory finite element analysis was performed on each design within PSTAEBL, using Quad-4 elements. Steady stress analysis did not include gasload effects.

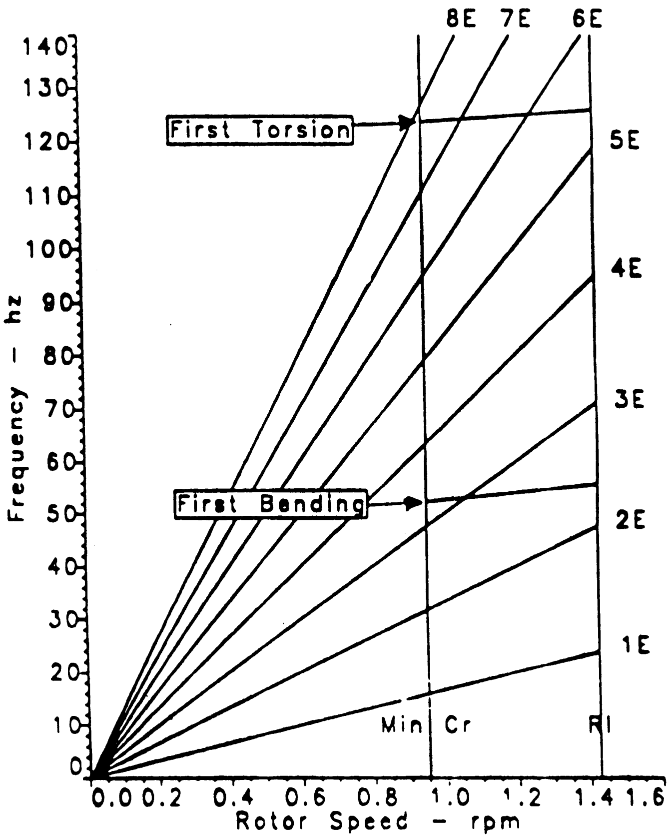



Figure 19.- First Generation ADP Fan Resonance Experience. 17" ADP nacelle rig fan resonance diagram scaled to the low noise size.

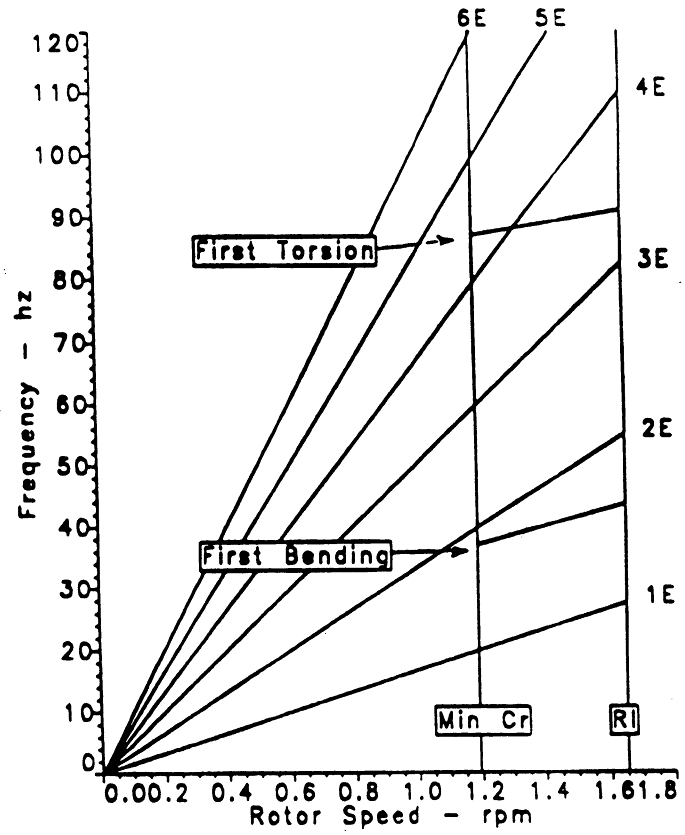



Figure 20.- First Generation ADP Fan Resonance Experience. 32" ADP TS-30 rig fan resonance diagram scaled to the low noise size.

## Analytical Results

Initially only the unswept design was examined. Forward and aft swept designs were analyzed after a successful unswept design was reached. Geometry modifications were made to the solid titanium unswept fan in PSTAEBL to tune the 3E/first torsion resonance above redline (Figure 21). Alterations to the camber and location of maximum thickness were explored; however, the tuning effort was not successful. Airfoil root choking concerns would not permit the thickness addition that would tune the torsional resonance. The torsional frequency could only be raised to 50% of the required level without impacting the aerodynamics. Tuning the resonance below minimum cruise was not allowed due to the stall flutter risk. A reduced velocity parameter was used to compare the stall flutter experience of solid titanium first generation ADP fans to the solid titanium first generation ADP fans and to the solid titanium design as shown below.

| Mode | Parameter | 17" ADP Nacelle Rig | 32" TS-30 Rig | Solid Titanium Low Noise ADP |
|---|---|---|---|---|
| Bending | $24W_1/bw_b$ | 2.7 | 3.9 | 4.1 |
| Torsion | $24W_1/bw_t$ | 1.1 | 2.0 | 2.3 |

The TS-30 parameter levels are considered acceptable limits to design to since the flutter was observed at the expected stall boundary. Based on this comparison, a solid titanium Low Noise ADP fan is expected to flutter, but raising the natural frequencies will alleviate this problem.

A spar/shell composite construction method was examined to perform the identical tuning task. The blade is made up of a titanium spar and is wrapped in graphite and fiberglass. Pratt & Whitney's prop fan and ADP demonstrator blades use similar constructions. Figure 22 compares the results of the composite blade analysis to the baseline solid titanium design. This design has frequency margin at redline on the 3E/first torsional resonance. Additionally, adequate 2E/first bending resonance margin was maintained at minimum cruise. Bending and torsional stall flutter parameter levels met the TS-30 limits as shown below.

| Mode | Paramter Limit | Composite Low Noise ADP |
|---|---|---|
| Bending | $24W_1/bw_b < 3.9$ | 3.6 |
| Torsion | $24W_1/bw_b < 2.0$ | 2.0 |

Airfoil weight was reduced by 50%. Because of time constraints, solid composite construction was not examined although it should not be ruled out.

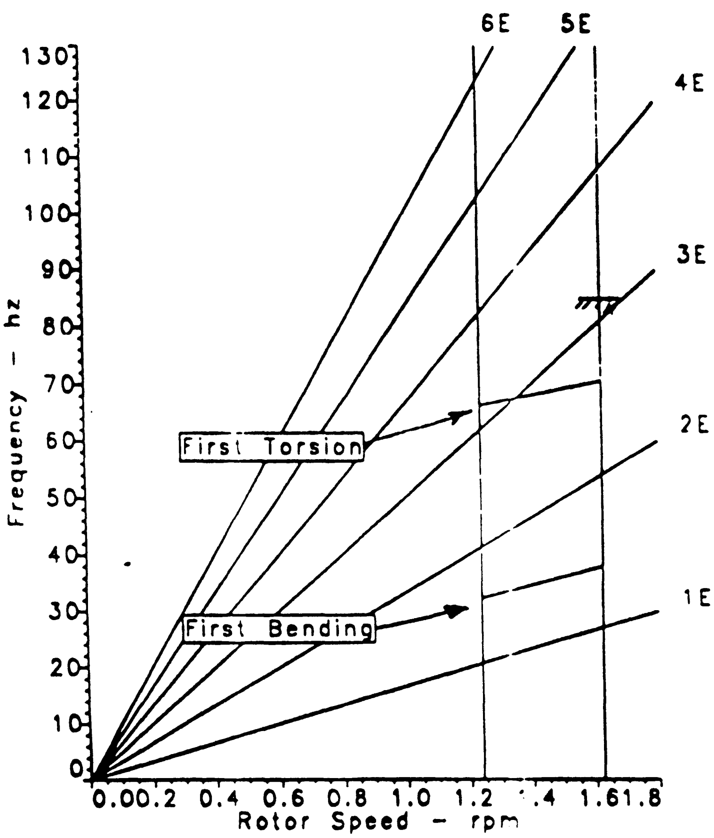



Figure 21.- Solid Titanium Blade has Low Natural Frequencies. Solid titanium unswept blade resonance diagram

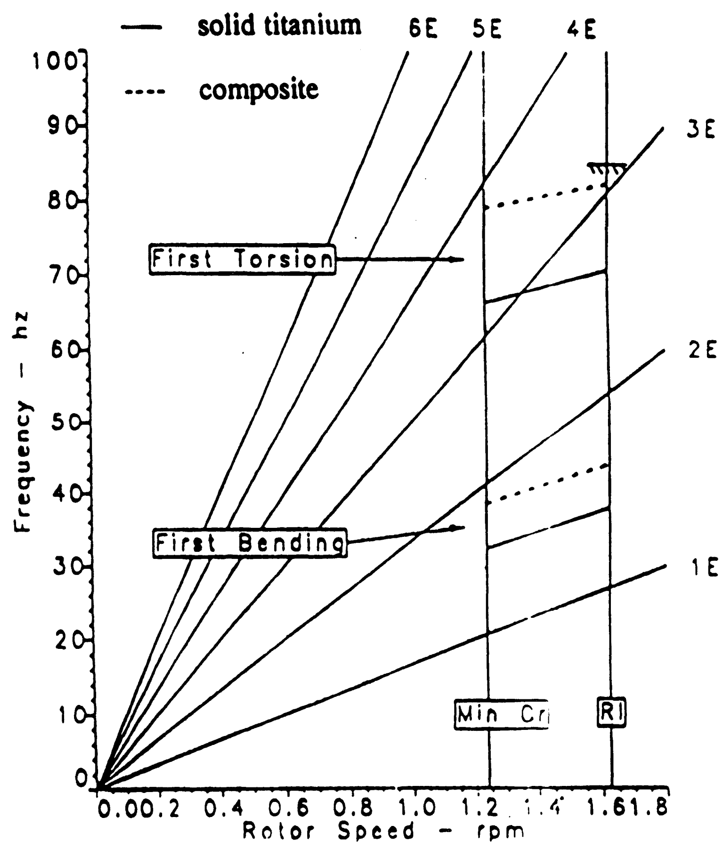



Figure 22.- Composite Blade Resolves Tunes 3E/First Torsion Resonance. Composite vs baseline blade resonance diagram.

Solid titanium forward and aft swept fan designs showed the same resonance and flutter problems identified in the baseline unswept design (Figure 23). Also, these designs have high steady stresses above the 0.2% yield strength at the peak location. The peak occurred along the leading and trailing edge for the forward and aft swept designs, respectively. A comparison of the swept fan stall flutter parameter levels and steady stresses to their respective limits is shown below. Composite construction should be examined to achieve a structurally acceptable design.

| Mode | Parameter Limit | Forward Swept | Aft Swept |
|---|---|---|---|
| Bending | $24W_1/bw_b < 3.9$ | 4.3 | 4.7 |
| Torsion | $24W_1/bw_b < 2.0$ | 2.9 | 2.9 |
| Steady Stress | 110 ksi | 169 ksi | 118 ksi |

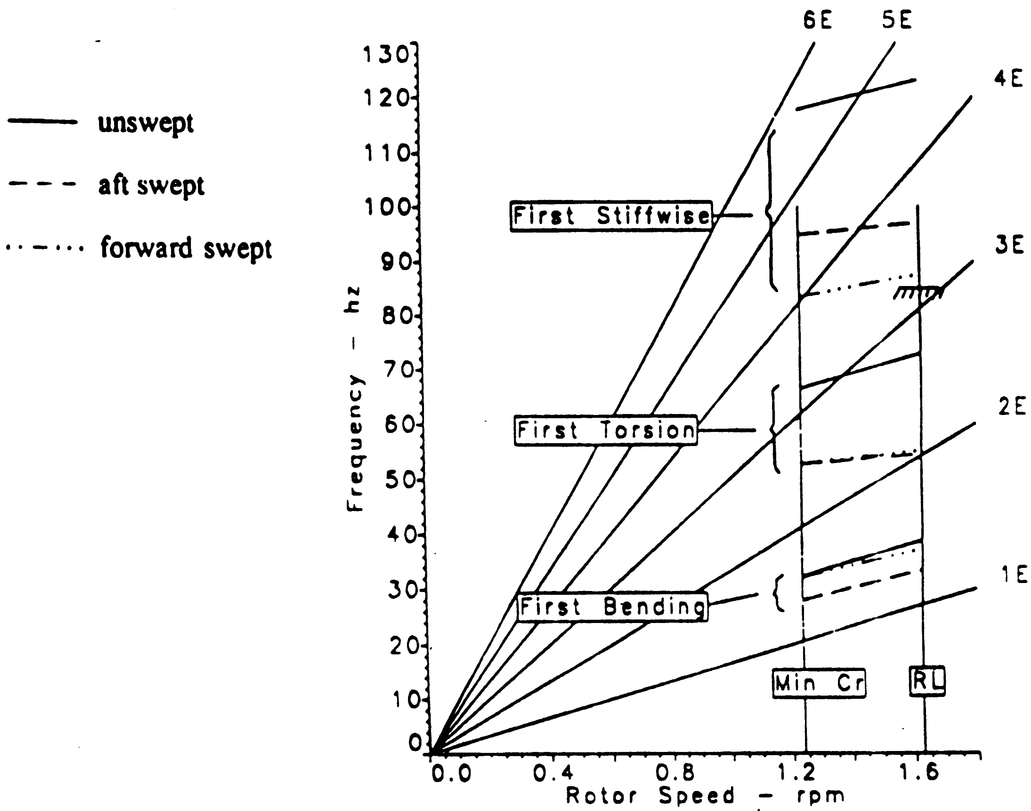



Figure 23.- Swept Solid Titanium Blades Have Low Natural Frequencies. Low noise ADP - swept blades vs baseline blade resonance diagram.

## Conclusions and Recommendations

### Conclusions

- Composite airfoil construction is necessary for Low Noise ADP rig fan blades.

- The spar/shell construction method is capable of yielding a structurally acceptable design without impacting the aerodynamic shape.

o Further investigation should be made on solid composite construction to see if further benefits could be gained.

Recommendations

o Analyze, fabricate and test a composite fan design that reduces the risks associated with a solid titanium design. This effort would gain valuable dynamic stress and stall flutter data as listed below:

  a) dynamic stress data that is scalable to low density designs
  b) dynamic stress data for distorted inlet dynamic stress prediction calibration.
  c) stall flutter prediction data.

o Perform soft body F.O.D. testing to assess the composite design's durability and gain calibration data for impact damage anaysis.

NACELLE AERO

Introduction

The nacelle aero portion of Task V concentrated on the evaluation of nacelle designs for Advanced Technology Engines that produced enough thrust to power large over-the-water, twin-jet transports but has a nacelle maximum diameter that is constrained to allow installation under the wing. Constraining the nacelle diameter results in nacelle designs that requires technology advancement or innovative design concepts to meet performance and operability requirements. Comparisons between constrained and unconstrained diameter nacelles (the latter meets performance and operability with today's technology but exceeds maximum diameter) resulted in identifying potential problems that technology advances need to overcome. Advanced concepts and research programs to establish concept feasibility are presented in this section.

Technology Evaluations

A nacelle design was established for a current technology unconstrained diameter baseline. Unconstrained, the nacelle diameter allows freedom in allowing enough gentle curvature in the inlet and nacelle cowl to meet operability and performance requirements. The inlet geometric features were determined from semi-empirical correlations based on current technology. The inlet throat area was sized to pass the maximum airflow while maintaining inlet pressure recovery (Ptl/Pto = .997). Takeoff angle of attack capability of 23.6° was set as a ground rule (current twin wide body aircraft operations). Pratt & Whitney design methods, used to generate the current technology inlet design, established correlations that related the highlight to throat area ratios to airflow and angle of attack. For a given airflow, increasing angle of attack capability was obtained by increasing lip thickness (highlight to throat area). Once the inlet highlight diameter was established, the external diameter was determined by second segment climb windmilling, ETOPS or cruise performance requirements. All three conditions were evaluated to determine which requirement was most critical.

Windmilling angle of attack is a function of windmilling mass flow ratio and windmilling cowl angle ( $\theta$ F). For a constant mass flow ratio, windmilling angle of attack can be increased by increasing the highlight diameter. This, however, impacts ETOPS in that peak surface Mach number is controlled by inlet highlight to maximum nacelle diameter ratio. These conditions suggests a gentle nacelle curvature which, with current technology, leads to thick, fat and long nacelle inlets. An example of these nacelle design curves is shown in Figure 24. However, thick, long nacelles are counter productive when cruise drag is considered. To illustrate, wave drag (shock losses) carpet plots (as a function of Dh/Dmax and L/Dmax were generated for a range of mass flow ratios and free stream Mach numbers, using a transonic inlet analysis, to determine the region of shock free contours or minimum wave drag (see Figure 25). The design intent for the current technology nacelles was to have shock free contours by ensuring that Dh/Dmax and L/Dmax are on the flat part of the curve which corresponds to thin lipped inlets. Meeting the operability and performance requirements resulted in a thick inlet, fat nacelle diameter of 166.5". To delay drag rise Mach number required lengthening the inlet. This diameter is 6.5" larger than what is allowed for installation under the wing of a large over the water, twin-jet transport, violating one of the basic ground rules of this study.

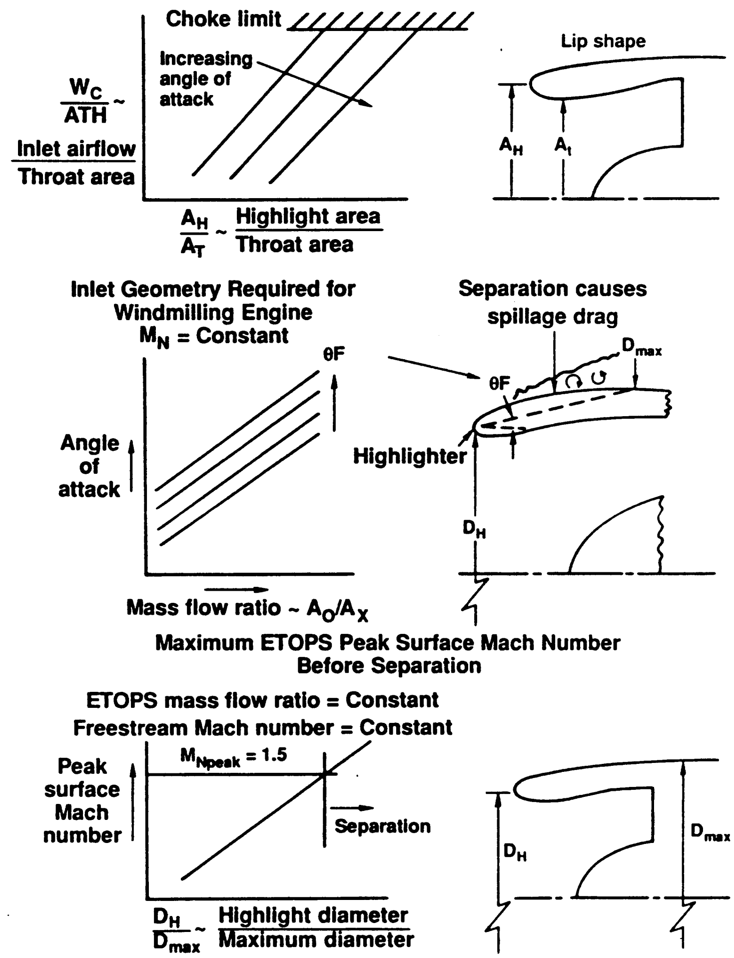



Figure 24.- Takeoff Angle of Attach Capability Before Internal Separation.

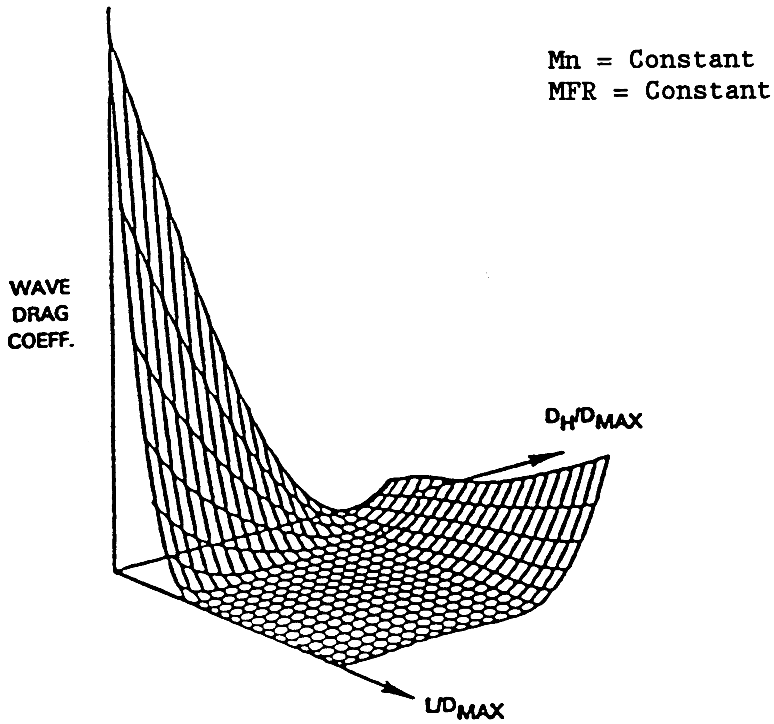



Figure 25.- Wave Drag Carpet Plot Defines Region of Shock-Free Contours.

Other options that constrained the maximum diameter to 160" were evaluated. Option 1 relaxed the inlet highlight to throat diameter rule necessary to achieve 23.6° takeoff angle of attack. This thinner inlet resulted in a design with 16.5° capability (before separation) using current technology. Also, constraining the nacelle maximum diameter increased the peak surface Mach number to 1.73 (from 1.5) for the ETOPS condition. This high Mach number will result in an increase of nacelle drag (due to flow separation) which could threaten "over the water" transcontinental capability. The inlet distortion also increased. This introduced another concern because fan designs require significantly reduced tip speed to achieve the acoustic goals. Lower fan tip speeds have less base surge margin which require separation free inlets with very low inlet distortion. Consequently, this option was considered too aggressive to meet the nacelle technology programs goals.

Several alternative nacelle parameter combinations were evaluated. The recommended nacelle that emerged from these considerations has the following features: a highlight to throat diameter ratio = 1.10; a highlight to maximum diameter ratio of .889 and a maximum nacelle diameter of 160". This nacelle, using today's technology, would also compromise angle of attack and wave drag rise Mach number capability and increase ETOPS peak Mach number. However, with the recommended technology programs in combination with innovative design concepts and recent data from cooperative PW/NASA Lewis wind tunnel research with the 17" rig, it is felt that the nacelle operability and performance goals can be achieved.

The current technology nacelle, the initial aggressive nacelle design, and the recommended nacelle with today's technology are summarized in Table VIII. Areas of compromise needing the nacelle and technology advances are boxed. The compromise in angle of attack capability is not highlighted nor is it considered a major problem. Evidence from the recent NASA Lewis/P&W fan/inlet interaction rig test suggests that fan effects will increase angle of attack capability (before separation). This can be seen in Figure 26 where a comparison between flow through/remote suction inlet test results are compared to powered fan/nacelle rig test. Note that the current technology angle of attack correlations are based on flow-through test results. Based on this data, these design methods are now considered to be too conservative. The challenge therefore, lies in achieving low inlet distortion at angle of attack, delaying drag rise Mach number from .78 to .83, and reducing ETOPS peak Mach number from 1.76 to 1.5.

TABLE VIII.- NACELLE OPTIONS

| | Current Technology | | Recommended Option | |
|---|---|---|---|---|
| | Baseline | Option 1 | Option 2 | Technology Program Goals |
| Max Dia. ~ 160" | 166.5" | 160" | 160" | |
| Max Airflow ~ lbs/sec | 4245 | 4245 | 4245 | |
| Windmilling AOA ~ degrees | 17 | 17 | 17 | |
| Takeoff AOA ~ degrees | 23.6 | $\boxed{16.5}$ | 20.0 | 23.6 |
| ETOPS Peak, Mn | 1.5 | $\boxed{1.73}$ | $\boxed{1.76}$ | 1.5 |
| Wave Drag Rise, Mn | 0.83 | 0.83 | $\boxed{0.78}$ | 0.85 |
| Inlet Distortion Index $\frac{P_{t\,max}-P_{t\,min}}{P_{to}}$ | 0.40 | 0.50 | $\boxed{0.44}$ | 0.1 |

## Recommendation

Numerous concepts were explored which led to identification of nacelle technology programs for proposed testing. These include: 1) Active and passive boundary layer control (Figure 27) which will address angle of attack and ETOPS (windmill) requirements; 2) Variable geometry self acting vortex generators (Figure 28) which would reduce the separation threat at ETOPS (windmill) conditions; 3) Surface contouring to control rate of diffusion, both externally for wave drag rise and internally for reduced inlet distortion; and 4) Short inlet designs which have potential for low inlet distortion (based on PW/NASA Lewis testing).

The critical path (Figure 29) for the suggested technology programs will begin with concept formulation and aero design. Candidate test configurations will be defined based on PW/NASA rig inlet testing and CFD evaluations. The first series of tests will be low speed operability through-flow suction tests. The same models will then be evaluated for high speed performance and ETOPS.

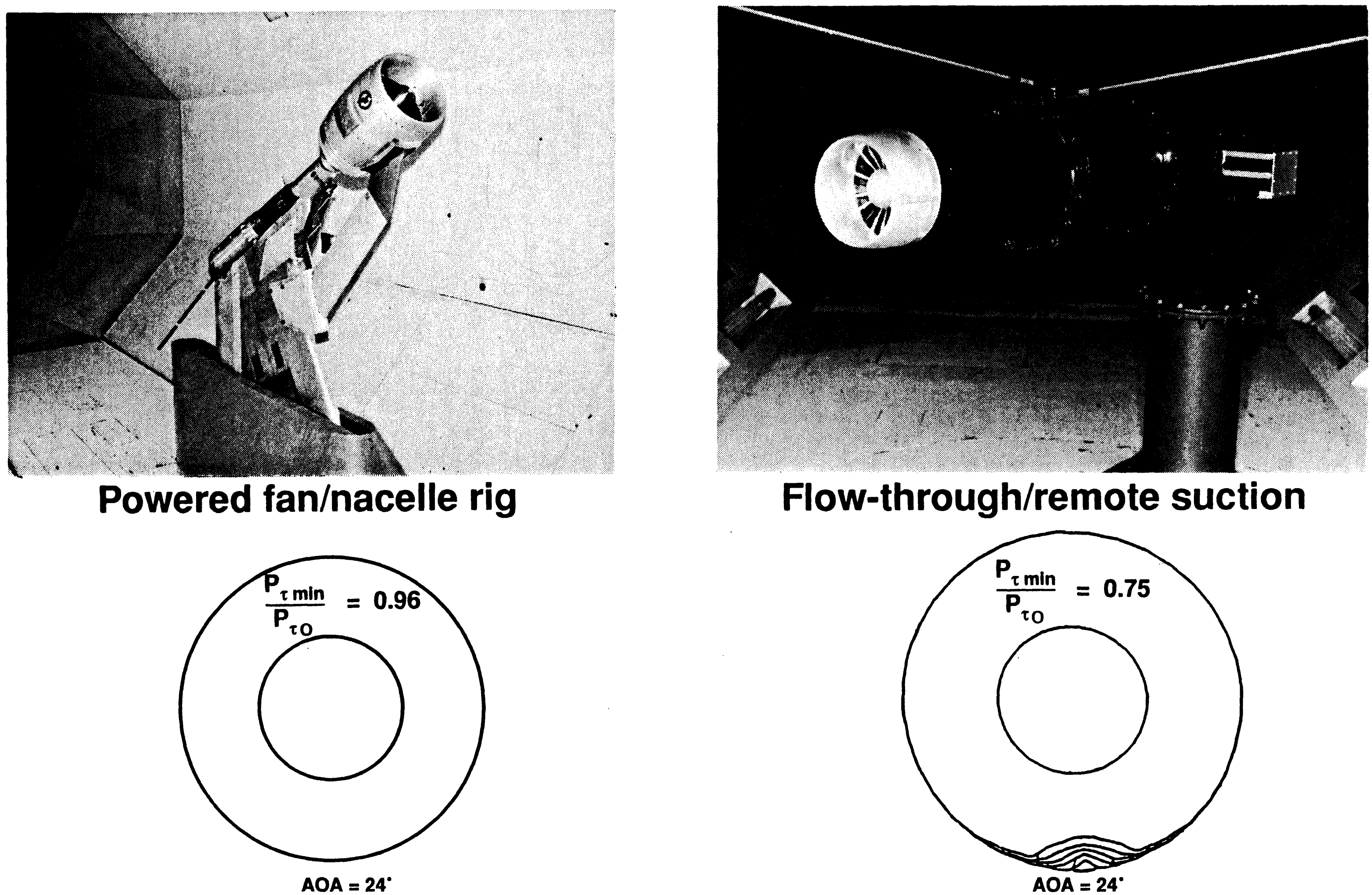



Figure 26.- ADP Fan/Inlet Interaction Rig Test Results Indicate that the Fan Operation Delays Inlet Distortion. The consequence is that analysis capability must be developed.

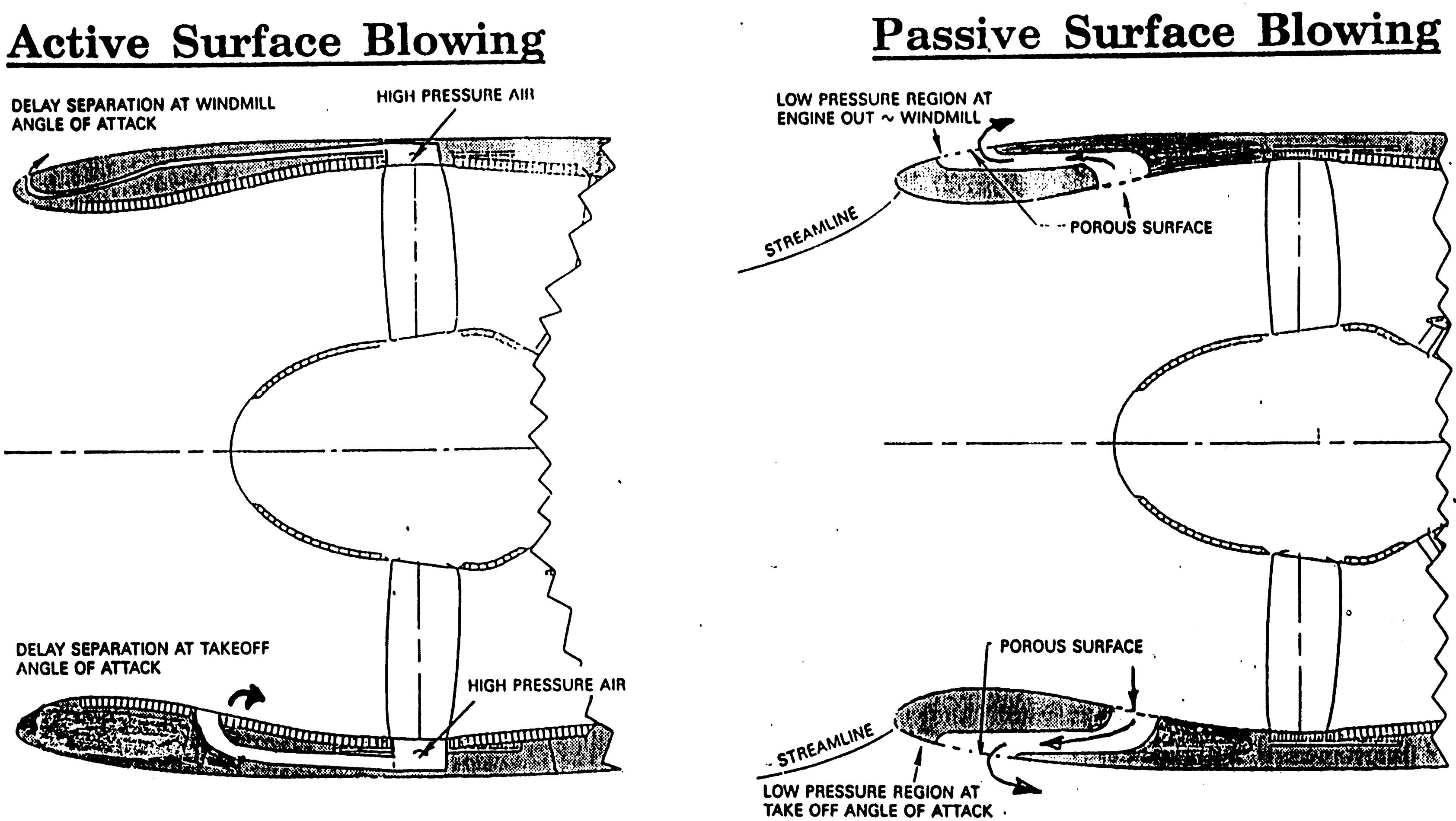



Figure 27.- Active And Passive Boundary Layer Control.

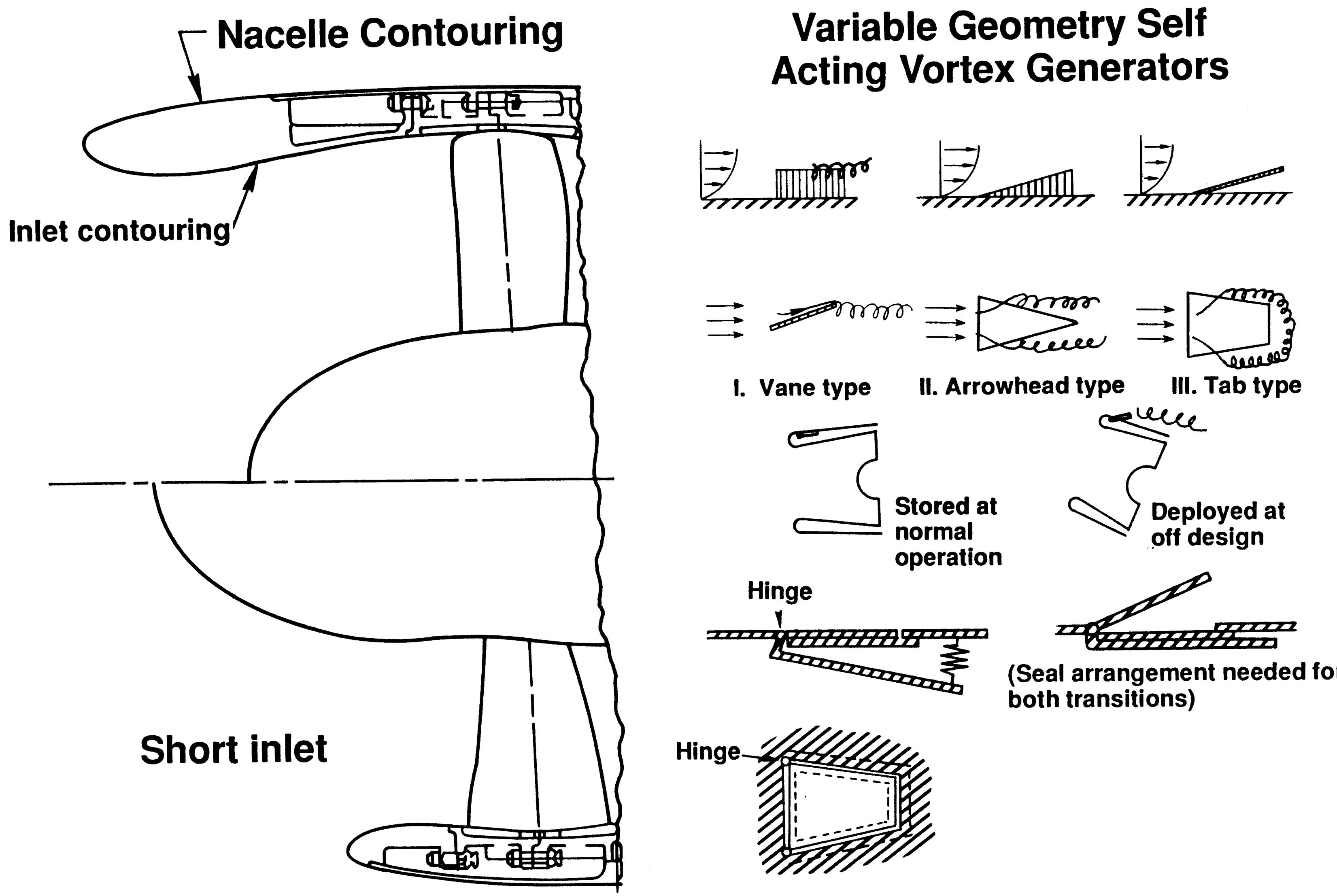



Figure 28.- Variable Geometry Self-Acting Vortex Generators.

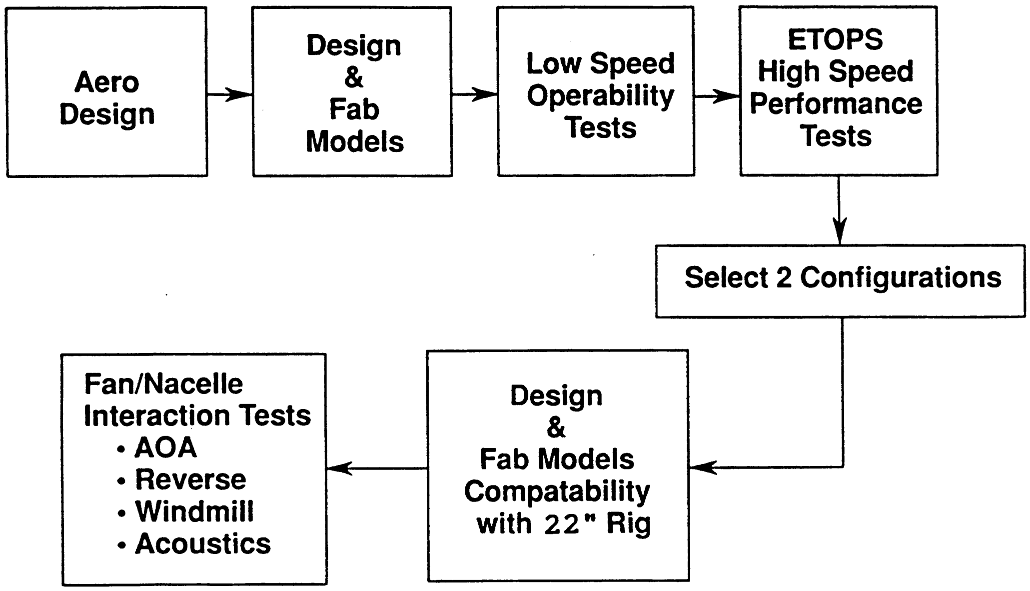



Figure 29.- Critical Path For Suggested Technology Programs.

At least two configurations will be selected for design, fabrication and testing with the 22" fan/nacelle interaction rig. These tests will be proof-of-concept tests where angle of attack (including inlet distortion), reverse, windmill (ETOPS) and acoustic tests will be conducted. It should be noted that the existing 17-inch rig may also be used as a test vehicle to evaluate the nacelle active and passive boundary layer control features mentioned above. Existing 17-inch inlet hardware can be modified, tested in less time and at lower cost than a new 22-inch rig, even though the 22-inch rig is the preferred approach. These tests will provide an opportunity to evaluate unique design concepts and provide development of innovative inlet and nacelle design technology.

Cooperative NASA/PW ADP test currently being executed or planned (Figure 30) complements the proposed program (described above) by supporting and addressing nacelle design methods that will be used in the nacelle aero design and concept formulations phase. The NASA Lewis 9'x15' ADP 17-inch rig Aero/Acoustic test began in 1990 and included angle of attack distortion, LDV reverse and acoustic testing. The impact of the fan on inlet angle of attack that was described earlier (Figure 26) will be further understood by testing the 17-inch rig inlets in a flow through suction mode. The primary objective of this NASA Lewis contract test is to develop methods that best simulate the presence of the fan for inlet suction distortion testing and thereby reduce the conservatism observed from previous test. The methods developed will be directly applied to a first series of proposed low speed, high angle of attack distortion flow through suction test. Recently concluded LDV reverse testing provided considerable insight to the global nacelle flow field in reverse.

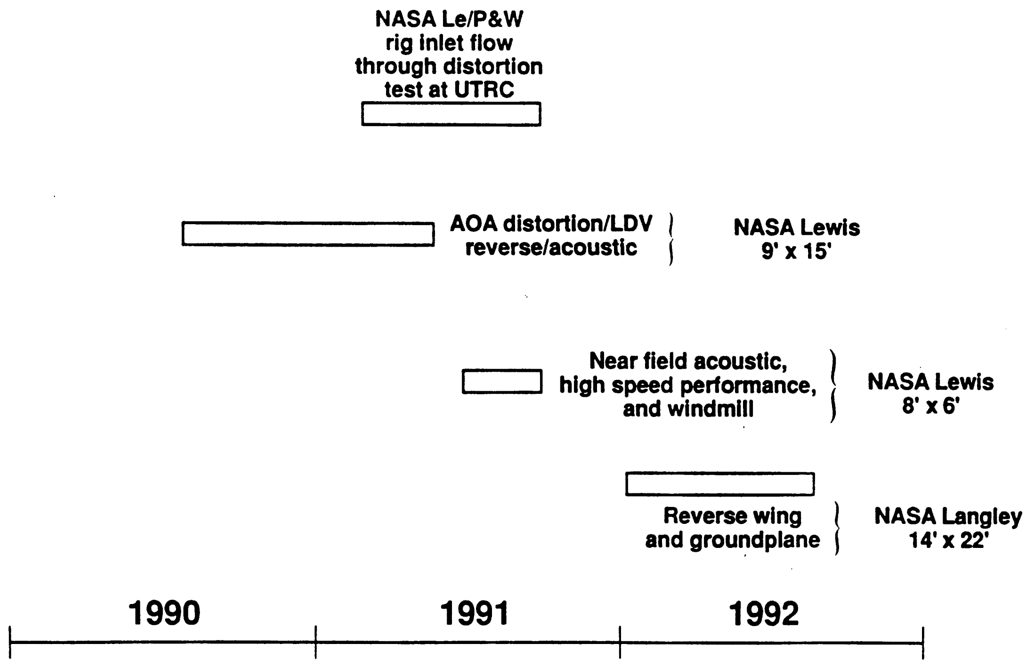



Figure 30.- Advanced Ducted Prop Planned Programs.

UTRC reverse tuft tests suggested a large separated region around the nacelle and this appears to be verified by the LDV reverse test. The LDV results obtained using NASA Lewis LDV system are shown in Figure 31. NASA/Lewis reverse test results have been especially useful in planning and executing the NASA Langley ADP 17" reverse test (in 1992) where the addition of wing and ground plane will be evaluated. High speed performance and windmill (ETOPS) and near field acoustic test have been conducted at NASA Lewis in 1991-92. The ETOPS windmill test data added the data base used in nacelle ETOPS sizing design methods. In addition, high speed nacelle performance differences between the current technology nacelle and the plug inlet have also been determined.

The inlet technology unique concepts and innovative features discussed above, were incorporated into test programs described in the following technology program plans section.

Nacelle Aero Technology Programs

Low Speed High Angle of Attack Test

The next generation fan designs will have low tip speeds and low fan pressure ratios to meet the noise goals. As a result, these fan designs require low inlet distortion to avoid fan surge. Inlet technology programs are required to meet constrained nacelle diameter and low inlet distortion requirements. The objective of this program is to determine the impact of technology concepts such as active and passive boundary layer control and inlet contouring on angle of attack capability (before separation) and inlet distortion (at AOA) entering the fan.

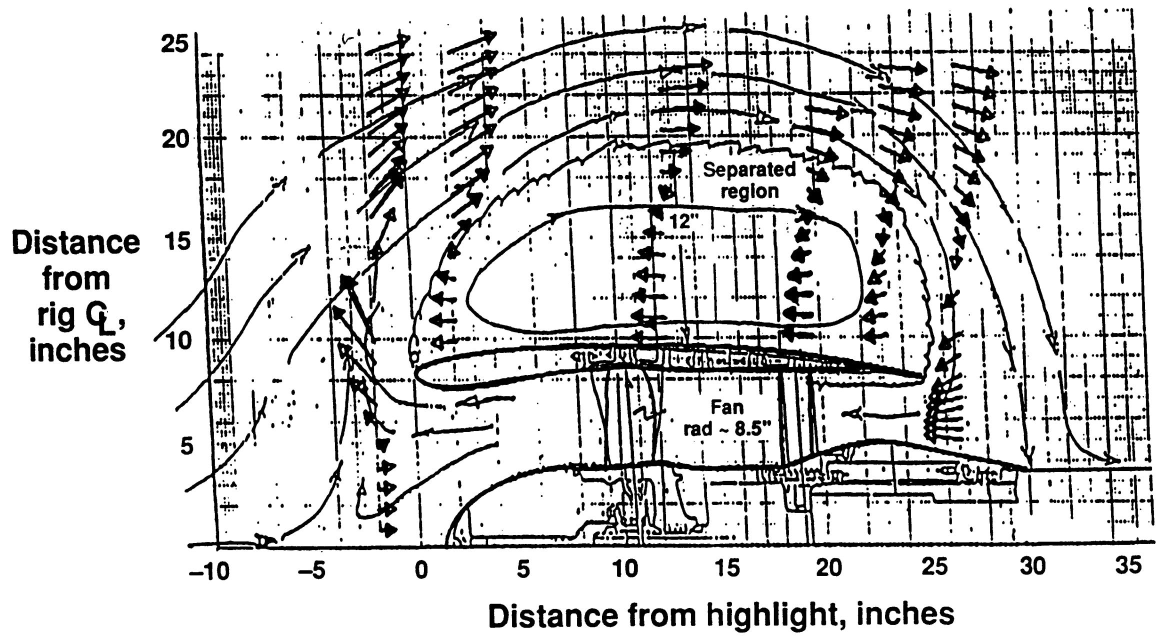
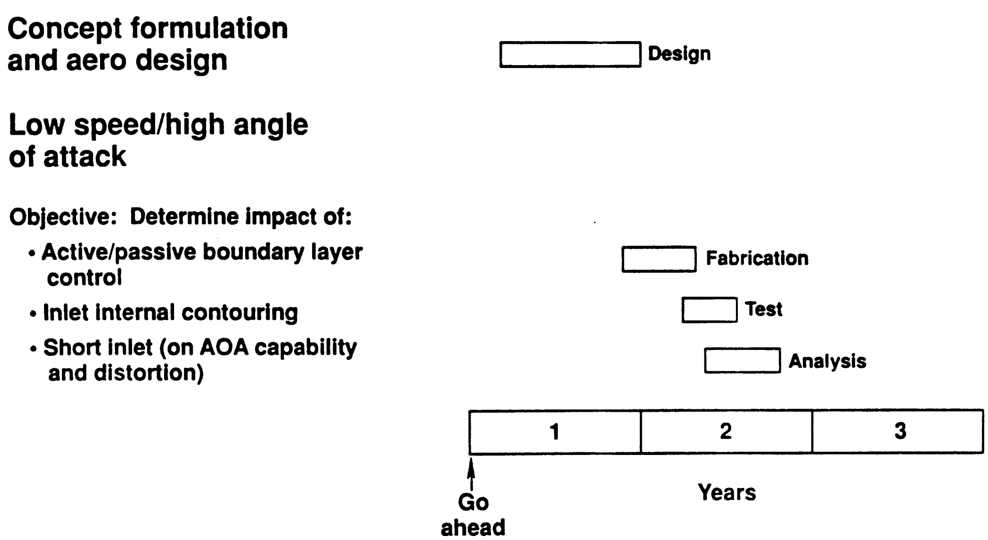



Figure 31.- Reverser Test Showed Large Separated Region that was Verified by LDV Reverse Test.

## Approach

This program will include testing several inlet concepts with flow through inlets (remote suction without fan) as shown in Figure 27 These tests would vary the amount of surface blowing, utilizing various angles of attack. In addition, internal inlet shapes will be varied to determine the impact on inlet distortion at angle of attack.

PROGRAM OBJECTIVES



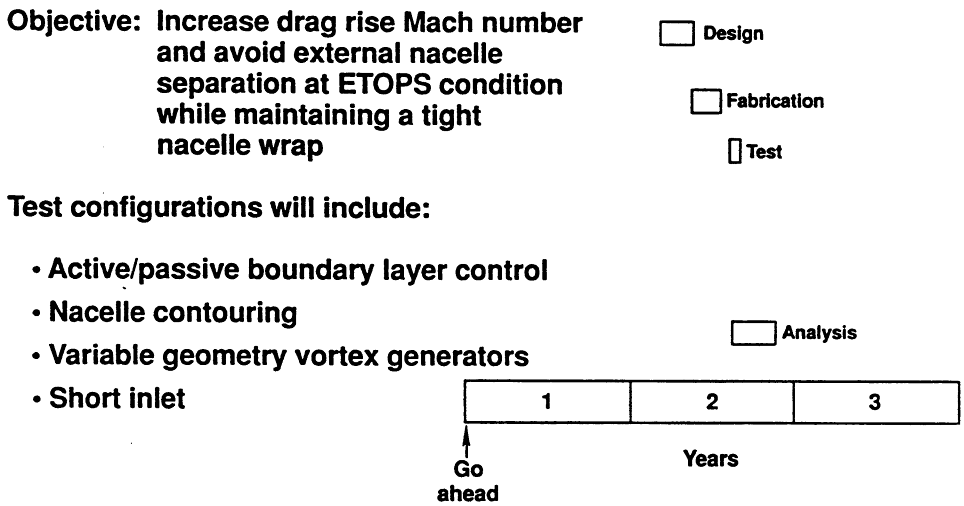
High Speed Performance and Windmill (ETOPS) Test

Constrained nacelle diameter requirements lead to tighter nacelle designs that do not meet ETOPS and cruise drag requirements using current design methods. Technology programs are required to meet cruise drag and ETOPS requirements. This program will identify external contours (controlled diffusion shapes, vortex generators) that will delay drag rise to higher Mach numbers and avoid external nacelle separation (ETOPS) with a tighter nacelle wrap.

Approach

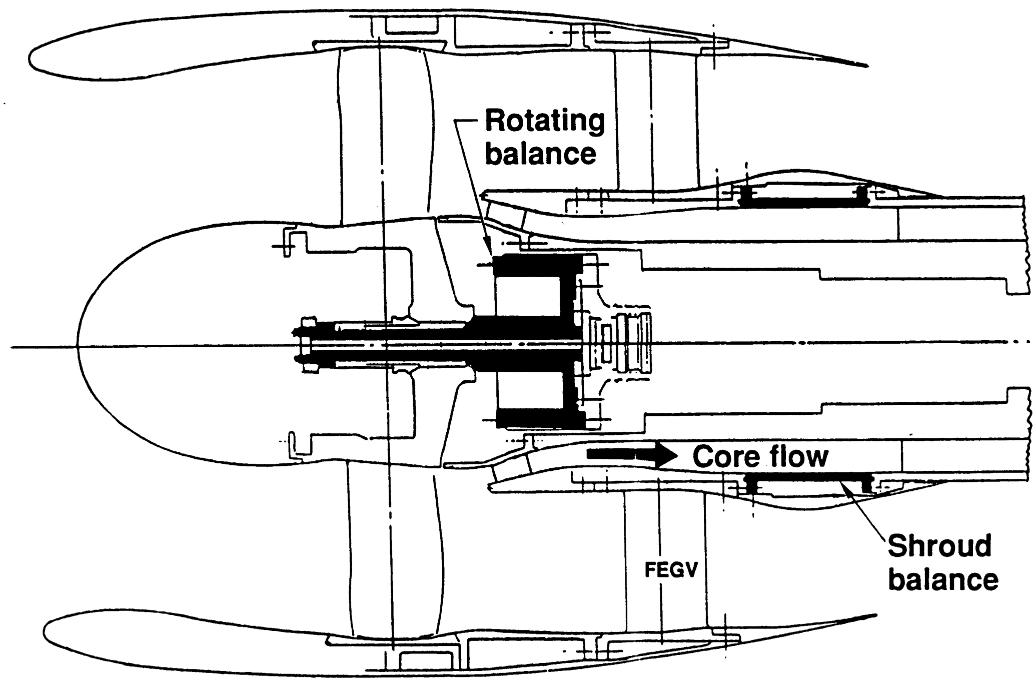
High speed flow through (without fan) performance and windmill test where nacelle drag will be measured. Test configurations will include external nacelle contouring and controlled diffusion surfaces (to eliminate stocks) for the performance test. For the windmilling (ETOPS) test, variable geometry vortex generators will be tested to delay cowl separation. In addition, surface blowing and suction will also be tested.

HIGH SPEED PERFORMANCE AND WINDMILL (ETOPS)
TEST WITHOUT FAN




ADP 22" Fan/Inlet/Core Flow Interaction Rig

Flow through (without fan) angle of attack and performance test will identify inlet and nacelle configurations that will meet operability and performance requirements. Selected configurations will then be tested with the 22" fan/inlet/core flow (Figure 32) rig as a proof-of-concept test. This test will include angle of attack, reverse, windmill and acoustics. The objectives of the inlet/fan test program are to :




Note: The actual internal and force balance geometry of the 22" rig is different from this early concept.

Figure 32.- 22" Fan/Inlet/Core Flow Interaction Rig

1. Verify inlet angle of attack capability and distortion levels of selected flow through inlets in the presence of the next generation fan.

2. Define fan surge margin with inlet distortion.

3. Establish fan reverse effectiveness (measure reverse thrust).

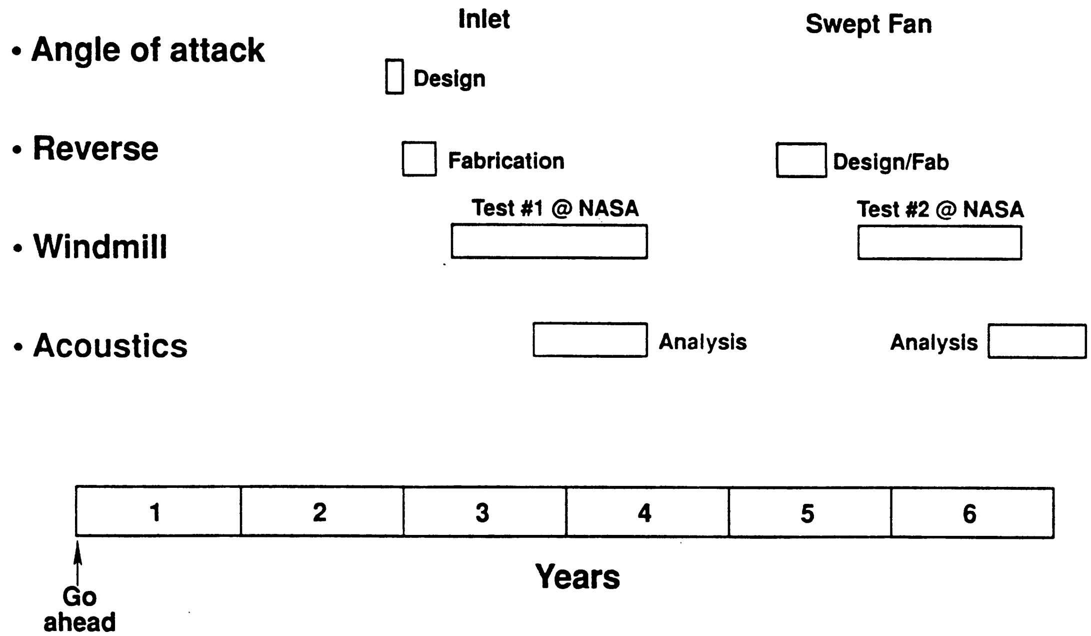
4. Determine reverse operability by measuring core inle airflow and pressure loss in reverse.

5. Verify windmill drag (ETOPS) nacelle configuration.

Approach

Five inlet/nacelle concepts will be tested as flow through models (with fan simulation) to identify configurations that will meet separation angle of attck and inlet distortion goals. In addition, high speed performance and windmill test will be conducted to meet cruise drag and ETOPS goals. Configurations that show the best performance will be selected and scaled to the 22-inch rig size for proof-of-concept testing. The 22-inch rig will have core flow and thrust balanced (Figure 32) so that operability, including reverse with core flow, and high speed windmill drag can be evaluated and compared to program goals.

ADP 22"FAN/INLET INTERACTION RIG TESTS




ACOUSTICS

## Current Noise Status

### Noise Goal

The primary noise goal of this study is to achieve a 5 to 10 EPNdB below FAR Part 36 Stage 3 noise limits at each of the three noise certification measurement stations.

Background -- Currently, some modern airplanes have been certified with margins below the limits that are within the goal range at one or more measurement conditions. This could give the false impression that technology now exists to meet the noise goal. For example, some airplanes with a high takeoff thrust/airplane weight ratio may have low noise levels relative to the rule at the takeoff condition, but small margins at the sideline condition. More importantly early versions of a new airplane family must certify with sufficient margins below the limits to allow for growth. Growth versions of an airplane have noise levels that increase with airplane weight much more rapidly than permitted by the increases in noise limits that are allowed as weight increases. Airplane/engine programs traditionally have been driven by the market to produce growth derivatives and the manufacturers depend on the derivatives for program economic viability. If the airplane weights were restricted to the initial lower weight, quieter versions and larger size (noisier) derivatives were not permitted, more flight operations would be required to carry the same number of passengers adversely impacting the community noise exposure.

The fuel efficient ultra high bypass ratio Advanced Ducted Propeller (ADP) engine configuration is expected to offer noise benefits which are the result of lower jet noise levels because of the lower jet exhaust velocities inherent with the high bypass ratios, and lower fan noise levels because of the reduced fan tip speeds. The fan noise benefits are offset to a degree by the use of shorter nacelle lengths (to reduce weight) that offer less opportunities for the use of sound treatments than in modern 5 to 6 bypass ratio engines, the larger size of the ADP fan, and the incentive for weight savings to reduce fan-to-exit-vane axial separation relative to modern engines.

Noise reduction technology advances are therefore necessary to assure that a full derivative family of an advanced, fuel efficient airplane/engine program can meet the noise goals of 5 to 10 EPNdB below the limits at each measuring station.

### Noise Prediction Methodology

To assess the noise status of study configurations relative to the program goals, noise prediction methodologies were used which accounted for fan noise, jet noise, and airframe noise at the approach condition. Previous studies of similar ADP configurations have shown that the compressor, combustor, and turbine noise sources are substantially lower in level (at least 10 EPNdB less than fan noise) and do not contribute to the total noise.

Preliminary fan noise estimates were produced by scaling from a PW4000 engine noise data base, entering at the appropriate fan tip speed and adjusting amplitudes for diameter, fan-to-exit vane spacing, and acoustic treatment differences between the base engine and ADP configuration. Jet noise levels were adjusted from the base by accounting for jet velocity and nozzle area differences.

More rigorous predictions were made using the P&W Flight Noise Prediction System which is a processing program that uses data bases and semi-empirical prediction methods to estimate component noise levels in terms of one-third octave band sound pressure levels, projects the levels to the desired flight condition, including Doppler effects where appropriate, and combines the 1/3 octave band sound pressure levels from the different components, ultimately producing an EPNDB value for the engine and airplane performance and geometry inputs. Fan noise predictions in this system were obtained from a full scale data base established from scaled ADP model data.

#### Baseline Configuration

Preliminary noise estimates for the baseline, constrained diameter, configuration resulted in only nominal compliance with Stage 3 limits primarily because of the higher fan tip speeds associated with the constrained diameter configuration.

Lower Tip Speed Configuration

A new constrained diameter configuration was defined with lower fan tip speeds to reduce noise. The tip speed reductions with the new cycle were large (e.g., reduced from 1279 ft/sec to 966 ft/sec at the sideline condition). Geometry features of the lower tip speed configuration that can significantly influence noise are as follows:

| | | |
|---|---|---|
| Fan diameter | = | 140.0 inches |
| No. of fan blades | = | 16 |
| No of exit vanes | = | 34 |
| Mid Span fan T/E to FFEGV L/E spacing | = | 1.8 fan blade chords |
| Inlet acoustic treatment | = | 0.9 length/height ratio fan exhaust |
| Flowpath treatment | = | 2.2 length/height ratio |

Noise levels for the low tip speed cycle were estimated using both the preliminary and rigorous prediction systems. These predictions are summarized in Table IX. Margins below Stage 3 limits were predicted to be 4 to 7 dB at each condition. Comparisons of key acoustic parameters and estimated noise levels for a modern conventional turbofan, the base constrained diameter ADP, and constrained diameter, reduced tip speed ADP installations are shown in Table X. The comparisons are for the sideline case and a fixed mission is assumed. For a fixed mission, the aircraft powered by the STF940 current turbofan engine is heavier (750K lbs TOGW) than the ADP powered airplane (650K lbs) because of the additional fuel carried by the less efficient turbofan powered airplane. Noise levels estimated for the turbofan powered airplane are similar to the base ADP predicted levels. Although the base ADP has lower fan tip speeds than the turbofan, the noise reduction benefits are offset by the larger diameter and closer fan-to-FFEGV spacing of the ADP. The significantly lower tip speeds of the reduced tip speed ADP configuration offer clear acoustic benefits.

TABLE IX. - ESTIMATED NOISE LEVELS

Lower Tip Speed Cycle
Fan Diameter = 143.1" TOGW = 650,000

| | Cutback | Sideline | Approach |
|---|---|---|---|
| Net Thrust (lbs) | 50,302 | 72,682 | 21,841 |
| Tip Speed (fps) | 861 | 966 | 634 |
| Altitude (ft) | 1600 | 1783 (slant) | 394 |
| Stage 3 Margin (EPNdB) | 4 to 6 | 5 to 7 | 4 to 5 |
| Cumulative Margin | = 14 to 17 | | |

TABLE X. - COMPARISON OF KEY PARAMETERS AND RESULTING NOISE ESTIMATE

| | Current TF STF 940 | Base ADP | Reduced TS ADP |
|---|---|---|---|
| Takeoff Gross Weight - lbs | 705K | 650K | 650K |
| Fan Diameter - inches | 126 | 140 | 143 |
| Fan Tip Speed - ft/sec | 1450 | 1279 | 966 |
| Midspan Fan-FFEGV Spacing (spacing/chord) | 2.4 | 1.8 | 1.8 |
| Aft Treatment L/ | 1.8 | 1.8 | 2.2 |
| Estimated Sideline EPNL | 102 | 101 | 96 |
| Stage 3 Limit - EPNL | 102.2 | 101.9 | 101.9 |
| Margin | ~0 | ~1 | ~6 |

- o Relative to the current turbofan, the noise reduction benefits of the lower tip speed Base ADP are offset by the closer fan-to-FFEGV axial spacing and the larger diameter fan.
- o The significantly lower tip speeds of the reduced TS ADP offer a clear acoustic advantage.

---

The relative importance of key components for the constrained diameter, reduced tip speed ADP configuration is summarized in Figure 33 for both treated and hardwall configurations. The predominance of the fan as a noise source is apparent. Figures 34, 35 and 36 present for the sideline, cutback, and approach conditions, respectively, fan, jet, airframe and total noise directivities in terms of tone corrected perceived noise level (PNLT) vs flyover time. The predominance of aft radiated fan noise is apparent. Noise reduction technology advancements are needed in order to achieve the desired goal of 10 EPNdB margin below Stage 3 at each condition. The noise predictions indicate that noise reduction programs should address fan noise sources. As shown in Table XI, further applications of current technology fan noise reduction methods could be considered to obtain the desired noise reduction. However, more extensive use of these methods would results in unacceptable performance, weight and cost penalties. Selection of specific fan noise reduction technologies that offer the most promise for a significant payoff is addressed in the following section.

TABLE XI.- APPLICATION OF CURRENT TECHNOLOGY TO FURTHER REDUCE NOISE FROM CONSTRAINED DIAMETER, REDUCED TIP SPEED CONFIGURATION

| Methods | Estimated Benefit (Cumulative EPNdB Reduction) |
|---|---|
| 1. Further Tip Speed Reduction | |
| o 10% reduction | 6 |
| o 20% reduction | 11 |
| 2. Additional fan-to-FFEGV Spaciang | |
| o 50% increase | 4 |
| o 100% increase | 7 |
| 3. Additional Treatment Area | 7 |
| o 25% increase | 3 |
| o 50% increase | 5 |

Note: Unacceptable performance, weight, and cost penalties are likely from application of these methods.

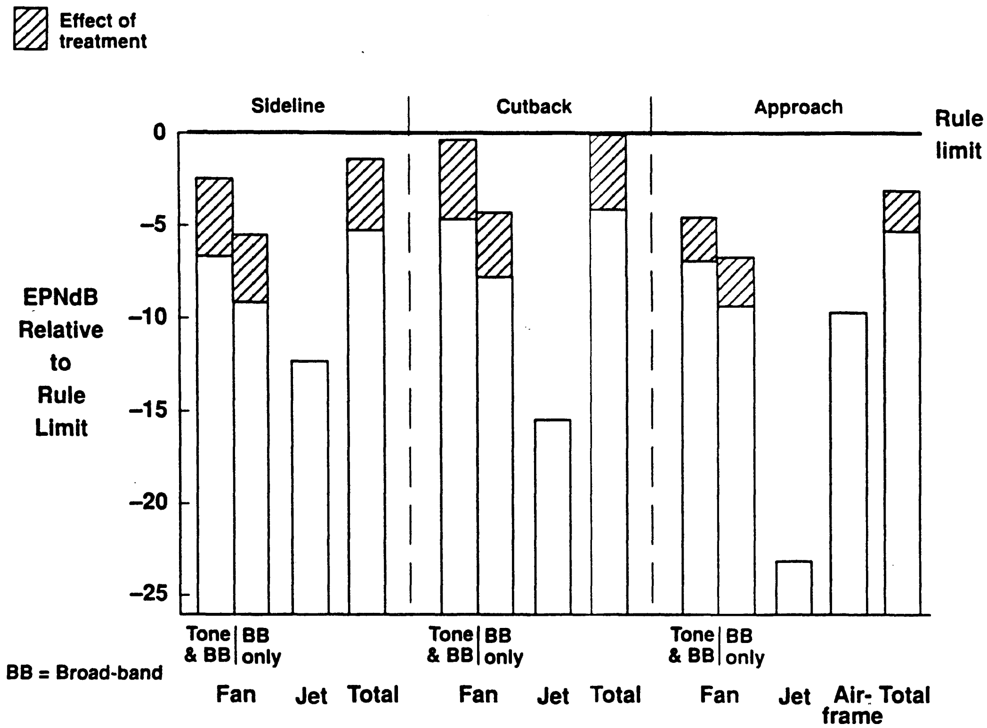



Figure 33.- Estimated Relative Source Noise Levels. Constrained diameter, reduced tip speed - ADP configuration.

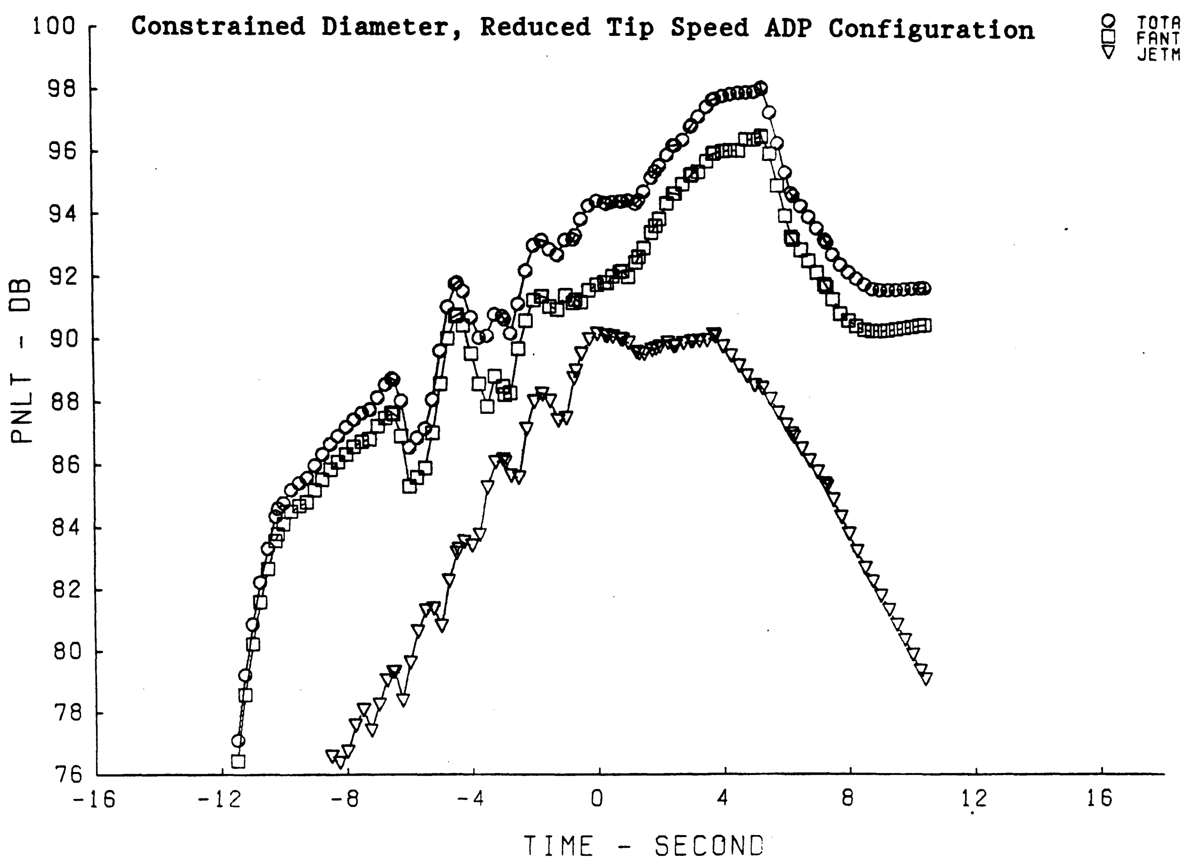



Figure 34.- Sideline PNLT Time History.

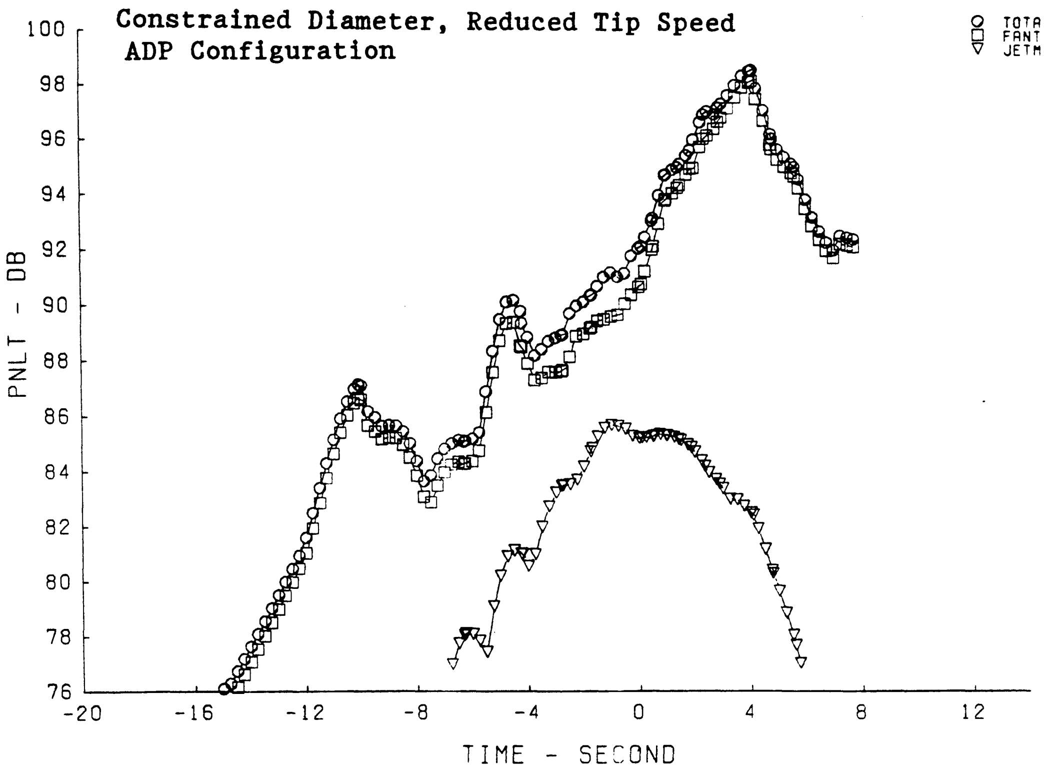



**Figure 35.– Cutback PNLT Time History.**

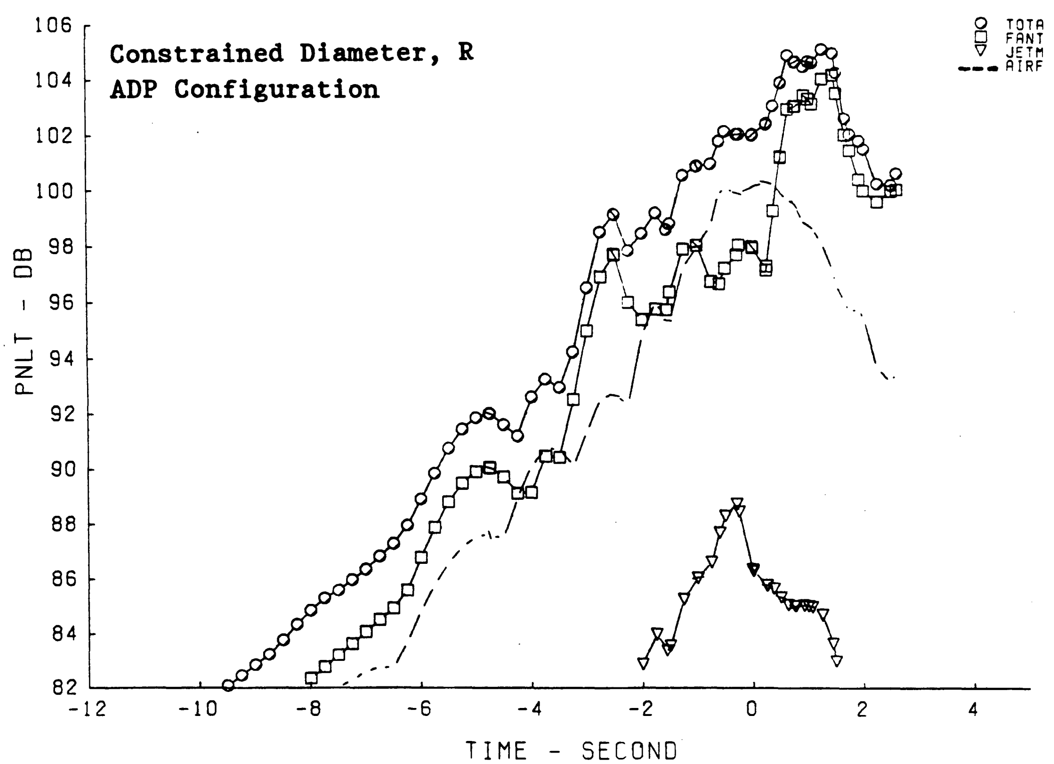



**Figure 36.– Approach PNLT Time History.**

## Selection of Low Noise Technologies

### Candidate Selection

To reduce noise from the dominant fan source in an ADP configuration, approaches and concepts were defined that might offer a noise reduction payoff. The candidates were divided into two categories: Source Noise Reductions (Figure 37), and Reductions from Treatment and Propagation/Radiation Mechanisms (Figure 38). Within these categories the candidate approaches were further identified as offering potential reductions in tones and/or broadband noise.

| | | Tones | Broadband |
|---|---|---|---|
| (1) Theoretical Modeling of Fan Geometry and Performance Effects | Reduced Tip Speed | X | X |
| | Increased Spacing | X | |
| | Optimized V/B Ratio | X | |
| | Leaned/Canted FEGV'S | X | |
| | Swept Fan Blades | X | |
| (2) | Fan Tip Casing Treatment | X | X |
| | Inlet Boundary Layer Control | X | X |
| | Blade Trailing Edge Blowing | X | X |
| | "Wheeler" VG's on Blades | X | X |
| | Rippled Trailing Edges | X | X |
| (3) | Active FEGV Lift Control | X | |
| | Passive Lift Control | X | |
| | Stator Bypass System | X | X |

Figure 37.- ADP Noise Reduction Technologies - Source Noise Reductions.

| | | Tones | Broadband |
|---|---|---|---|
| (4) Advanced Liner Development | Optimized Treatment Tuning | X | X |
| | Multiple Layer Treatment | X | X |
| | Bulk Absorbers | X | X |
| | Treatment Segmenting(Axial/ Circumferential | X | X |
| | In-Situ Treatment Impedance Control | X | X |
| | Active Treatment Impedance Control | X | X |
| | Active Noise Control | X | X |
| | Inlet/Aft Shields | X | X |

Figure 38.- ADP Noise Reduction Technologies. Reductions from treatment and propropagation/radiation mechanisms.

Source noise reduction candidates included several methods for affecting the generated unsteady airfoil pressure distribution on the rotor or stator by either reducing the strength of the incoming wake or the airfoil response to the wake. Reduction candidates from treatment and propagation/radiation mechanisms refer to methods for reducing the noise in the duct once it has been generated. These methods can be categorized as either advanced acoustic treatment design approaches that offer potential for more attenuation, or methods for beaming the noise away from the observer (e.g.inlet and aft shields).

Candidates that were judged as meriting further research were selected based on particular noise reduction potential, probability of successful development of the approach, timing (i.e. medium to long term development program), and possible long term capabilities of the approach. Figure 37 shows the source noise reduction candidates selected for further development. Although the three items in Figure 37 are commonly used to reduce noise, theoretical methods for accurately predicting the effect on noise of vane/blade ratio or increased spacing do not exist. If improved theoretical methods could be developed and validated, acoustic designs could be optimized resulting in further noise reductions. In addition, improved prediction system capabilities would provide the means to evaluate noise reduction benefits from leaned and canted FEGV's or from fan sweep effects. The lack of appropriate theoretical tools has made it necessary to depend significantly on engineering judgement in selecting the more promising noise reduction candidates. Thus, development of theoretical methods is considered a high priority.

Various types of advanced fan tip casing treatment have been developed to improve fan surge margin and operability characteristics. These casing treatments are thought to affect fan noise. With the new casing treatments being necessary on an ADP it is desirable to experimentally assess potential for acoustic benefits.

Active noise control is a project being actively pursued as a method for reducing tone noise from a fan exit guide vane. Proof-of-concept has been demonstrated both numerically and in a test program. Significant additional effort is required to make this a viable method to reduce noise, and is therefore considered a prime candidate for a suggested program.

Other items on this list were also considered but were judged to be unsuitable for further study primarily because they lacked significant potential benefit relative to the development cost or because of the uncertainty of their successfully achieving the potential in a viable manner. Figure 38 lists possible suggested programs for reductions from treatment and propagation/ radiation mechanisms. Liners have often been a good method for reducing already created noise. In addition to the need to develop liner designs that are more effective, the slow turning ADP fans with fewer blades results in the need to suppress tones at frequencies that are lower than current experience. The fourth suggested program addresses many of these issues.

### Current Fan Source Noise Analytical Status

Analytical fan noise prediction systems have historically been inaccurate and unreliable at best. Present state of the art in fan noise prediction is limited to semi-empirical wake models combined with idealized vane/blade sets and constant area annular ducts. These methods have not been able to reliably predict even the most basic effects such as the influence of vane/blade ratio and blade to vane axial spacing. A reliable prediction system would allow for these effects to be quantified.

A reliable prediction system might also allow for tone noise reductions from other methods such as bowing, leaning, or canting vane sets or through fan blade sweep. This may be accomplished through the following methods. If a straight fan blade were assumed, the phases of the vane unsteady pressures might be optimized over a speed range to minimize the fan tone noise coming from the vane. This can be done by leaning, canting, or bowing the stators. The same effect could be obtained through a combination of fan blade sweep and vane leaning, canting, or bowing. This concept is possible in principle but needs to be analyzed and tested.

## Suggested Programs

Advances in fan and nacelle noise reduction technology are necessary in order to achieve significant (5 to 10 dB) improvements in the community noise exposure levels produced by airplanes powered by advanced ducted propeller (ADP) propulsion systems. The technology development should allow the improvements to be achieved in a viable, fuel efficient manner.

### Fan Noise Theory Development and Applications to Reduce Noise

This suggested program specifically addresses the development of analytical and numerical fan noise prediction methodology that can be applied to fan and FFEGV designs to obtain reduced levels of community noise.

The objective of this program is to develop and verify advanced methods for predicting fan wake/stator interaction tone noise. These methods will be used to optimize fan and FFEGV designs considering the effects of variables such as vane/blade ratio, leaned/canted fan exit guide vanes (FFEGV's) and fan sweep. These optimum designs will then be verified in a scale fan rig acoustic test program.

#### Approach --

ADP rig testing confirmed that the cut-on vane/blade ratio tested was noisier at blade passing frequency (BPF) than cutoff vane/blade ratio tested. However, theoretical analyses indicate that neither tested vane/blade ratio was optimum for minimum noise. In addition, no attempt was made to minimize noise through the proper phasing of unsteady vane pressures in such a way (e.g. vane leaning and/or canting) so as to cancel noise.

The suggested approach involves a joint program including the University of Missouri at Rolla, Hamilton Standard Division, United Technologies Research Center, and Pratt and Whitney. Advanced numerical methods will be developed to calculate tone noise due to fan wakes impinging on an FFEGV or core stator. A radiation method (developed by W. Eversman under contract to NASA) will also be further developed to predict propagation of this noise to the far-field. These methods will then be verified with fan rig and/or full-scale engine noise data. The elements of these methods will then be used in the design of fan blades and FFEGV's for low tone noise configurations. Such parameters as vane/blade ratio, vane leaning or canting, and fan sweep may be optimized for reduced noise. The most promising vane/blade designs will then be tested in a scale fan rig to verify the designs and the predicted noise reduction over the fan rig tip speed range. Additional vane/blade follow-up designs may be tested to provide further design guidance and verification of the prediction method.

Advanced Casing Treatment Testing to Reduce Noise

In a turbofan engine as fan tone noise is reduced, fan broadband noise becomes increasingly important. This suggested program specifically addresses the testing of advanced casing treatment to assess its impact on both fan tones and broadband noise, leading to reduced levels of community noise.

The objective of this program is to quantify the noise reduction potential of advanced casing treatment on fan tones and broadband noise.

Approach --

Advanced casing treatments have the capability of energizing the boundary layer so as to reduce the incidence of the flow on the fan blade tip. This is expected to reduce the strength of the fan wakes impinging on the downstream vanes in the tip region, thus reducing fan tones generated by this interaction. It is also thought that an important fan broadband noise source results from the high incidence the incoming flow makes with the fan tip. Thus, a fan broadband noise reduction also is expected from an advanced treatment.

For this task, advanced casing treatments being designed by the P&W compressor group for a scaled fan rig will be noise tested to evaluate and quantify the effect on fan tones and broadband noise. If fan noise reduction is observed, further work will be done to understand this noise benefit to further reduce fan noise using this type of casing treatment.

Development of Active Noise Control Methods to Reduce Noise

This suggested program specifically addresses the investigation of active noise control on a fan exit guide vane as a method for reducing fan noise leading to reduced levels of community noise.

The objective of this program is to develop and test methods to actively reduce fan tone noise being emanated from a fan exit guide vane (FEGV).

Approach --

This program would be a joint effort of the United Technologies Research Center and Pratt and Whitney. In an experimental program this past year it was successfully demonstrated that an actuated flap successfully can cancel the unsteady periodic lift on an isolated airfoil at low reduced frequency. In addition, a numerical study was performed in which two "pistons" placed on each vane in a cascade configuration successfully eliminated the noise from two propagating acoustic modes.

This proposed program is a follow-on effort of the above program and is intended to bring active control to the point of a fan rig test evaluation. An outline of experimental and analytical efforts required to accomplish this program is presented in Figure 39.

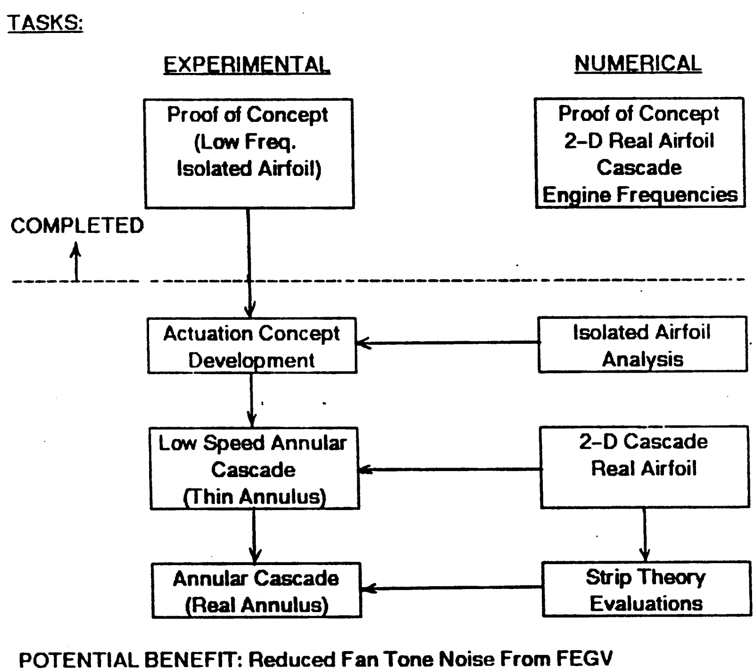



Figure 39.- Development of Active Noise Control to Reduce Tone Noise Generated at the FEGV.

During this program various actuator concepts will be investigated (eg. piezoelectric strips, etc.) and evaluated. The concepts chosen for further evaluation will be ones which might be used in a real engine configuration at real engine frequencies. The most promising concepts will be tested in the Active Noise test facility to better understand the actuator's behavior and effect on the noise in a simple laboratory environment. In addition, a low speed thin annular rig will be built to develop the actuators in a cascade environment.

To support this effort, a numerical program will be undertaken to assess the required size, location and actuation amplitude required for the actuators on an isolated airfoil and in a cascade. In addition, the present 2-D loaded cascade calculation method will be extended to a quasi-3D theory to evaluate the actuation requirements for an annular duct configuration.

Once actuators have been developed, they can then be tested on a scale fan rig if frequency response is not limiting. This testing will include the optimization of actuator locations and the evaluation of the actuators in an annular duct.

Investigation of Advanced Liner Concepts to Increase Noise Attenuation

This suggested program specifically addresses the development of advanced sound absorbing liner concepts that will offer more attenuation per unit area than current technology liners.

The objective of this program is to develop and assess methodologies for sound absorbing liner designs that are more effective than current designs and are applicable to the ADP. ADP configurations inherently have smaller inlet and fan duct length-to-passage height ratios available for lining applications than current modern high bypass ratio engine installations. Also, relative to current engines the ADP will have lower fan rpm's and fewer blades. This will result in the need to attenuate blade passing tones that are significantly lower in frequency than in current engines. To attenuate these low frequency tones current technologies would suggest liner backing depths that may be too large to be feasible. A 25% improvement in liner attenuation at current backing depths will be pursued.

Approach --

The planned approach is to evaluate advanced liner concepts in scale model tests. The first phase of this program will involve model and full scale tests to confirm the viability of conducting liner development in model scale. Liners that will be tested in the P&W full scale ADP demo engine will be tested in a scale version in the 22-inch diameter ADP fan rig. Results of model and full scale liner testing will be compared. Assuming that scale model liner testing will be validated, advanced concepts will be designed and fabricated for testing in the 22-inch diameter advanced ADP fan rig. Concepts that will be investigated will include optimally tuned liners, multiple layer designs, bulk absorbers, both axial and circumferentially segmented treatment and active control concepts such as impedance control. Results of the model testing also will be used to assess and upgrade analytical models. The advanced technology models would be used to design an "optimum" liner configuration that will be fabricated and tested in the large scale tunnel.

Estimated Benefits of Suggested Programs

Although the quantitative benefits of each of the suggested programs cannot be established reliably until the suggested program is performed, a qualitative assessment of program expectations was made. Table XII summarizes the results of this assessment which was based on engineering experience. The noise reduction benefits are shown in terms of cumulative EPNdB, which is the sum of the benefits at each of the three noise certification conditions. It can be noted that the total potential noise reduction coupled with the margins below certification limits predicted for the reduced tip speed configuration would result in achievement of the noise goals.

TABLE XII. - ESTIMATED BENEFITS OF SUGGESTED PROGRAMS

| Suggested Programs (in order of priority) | | Potential Noise Benefit (cum. dB) |
|---|---|---|
| 1. Theoretical Modeling of Fan Geometry and Performance Effects | | 5 to 8 EPNdB |
| o Swept Blades | (0 to 6 dB) | |
| o Optimized Vane/Blade Ratio | (3 t0 5 dB) | |
| o Leaned/Canted FFEGV's | (2 to 4 dB) | |
| o T/E Blowing | (3 to 8 dB) | |
| 2. Vaned Passage Casing Treatment (VPCT) | | 4 to 6 EPNdB |
| 3. Active Control | | 3 to 5 EPNdB |
| 4. Advanced Liner Concepts | | 3 EPNdB |
| o Bulk Absorbers | | |
| o Multiple Layers | | |
| o Segmenting | | |
| o In-situ Impedance Control | | |
| o Active Impedance Control | | |
| Total Potential | | 15 EPNdB |

Note: Benefits are not necessarily additive.

Summary of Acoustic Analyses

Noise assessment of a large (650,000 lb takeoff gross weight) twin engine airplane powered by an ADP engine having a constrained diameter and 25% lower tip speeds than current technology would specify, indicates a desired margin of 10 EPNdB below Stage 3 is not achievable with current noise reduction technology. Noise reduction programs have been identified that offer promise for potential payoff that are adequate to meet desired goals.

## SECOND GENERATION ADP PROPULSOR INTERACTIVE AERO/ACOUSTIC TESTING

This study has defined the propulsor (fan, inlet, nacelle) for a second generation ADP. Compared to the baseline ADP propulsor, the second generation propulsor with a 5 to 10 EPNdB reduction in noise requires a significant advance in component technologies.

All model testing to date of the ADP propulsor has been performed with the baseline design. Model testing of the components needs to be conducted for the second generation designs. The interactive performance of these components, along with noise characteristic, requires verification by wind tunnel testing utilizing an advanced interaction rig.

The objective of the test program are as follows:

- o Verify the uninstalled and low-speed installed interactive performance/operability of the second generation ADP propulsor (fan, inlet, nacelle) through wind tunnel testing of an Interaction Rig.

- o Measure noise levels relative to FAR36, Stage 3 and compare them to the goal of achieving a 5 to 10 EPNdB reduction at each of the three flight conditions, i.e. take-off, sideline, and approach.

<u>Program Approach</u>

The approach to verify the interactive aero/acoustic performance of the second generation ADP propulsor will be analogous to the approach taken to establish the baseline ADP acoustics and performance. First, technology programs will be conducted of each noise reduction component as required to verify the design parameters of each component. Second, the propulsor model comprising fan, inlet, and nacelle will be tested in low-speed and high speed wind tunnels to verify the interactive performance/operability of these components in an Interaction Rig. Based on initial results the design parameters will be changed to achieve the desired performance/operability and acoustic goals.

The design parameters for the second generation ADP are toward higher pressure ratio and weight flow per unit area. These parameters translate into more power requirements than were needed for the baseline diameter ADP Interaction Rig testing, creating a need for a new more powerful drive rig. This requirement is also needed because the diameter of the new ADP model will increase to 22" to facilitate inclusion of the core flow and splitter and to permit testing of acoustic lining in model size. Figure 40 compares the existing 17" Interaction Rig with the proposed 22" Interaction Rig incorporating the new test features. In the reverse mode, the splitter with core flow has a major effect on the flow field that enters the fan, thus affecting its starting characteristics. It is anticipated that diverting some of the flow to the core engine will further stall the fan and delay fan starting in the reverse mode. Simulation of the core flow also enables splitter design optimization for minimum losses and provides inlet profile data into the low-pressure compressor.

The test program that is proposed will be to:

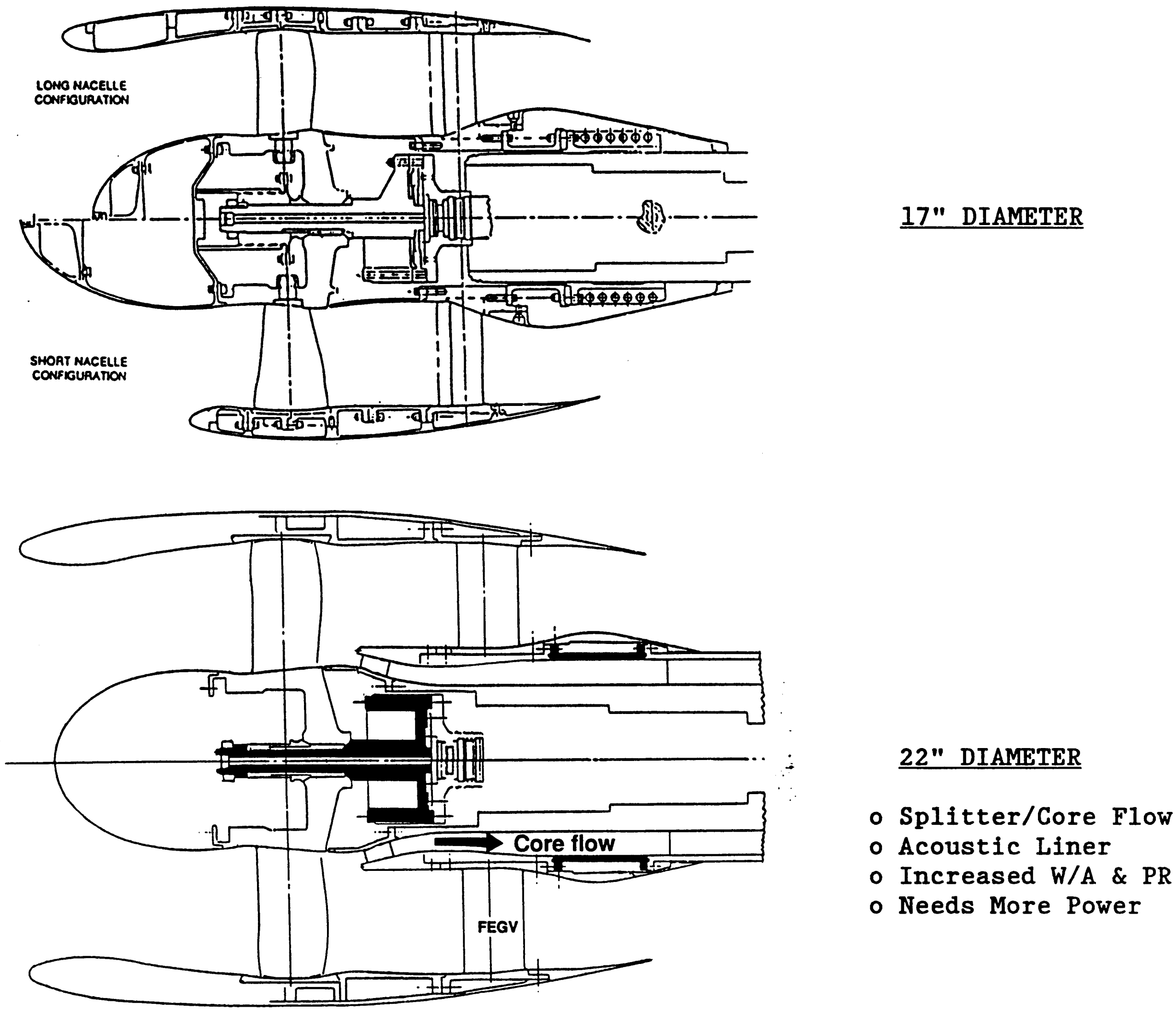
- o Perform fan, inlet, nacelle, exit nozzle, and overall nacelle performance/operability and acoustic testing at take-off, approach, and cruise flight Mach numbers with zero angle of attack.

- o Establish low-speed propulsor operability at angles of attack and tip treatments up to and including inlet separation and/or fan stability limit.

- o Determine effect of propulsor geometry on noise including acoustic liner effectiveness.

o Establish fan starting characteristics and reverse thrust operability and measure thrust in reverse including splitter with core flow; also, measure core flow inlet profiles and losses.

o Measure Windmilling drag at Mach numbers 0.5 to 0.8 at:.
  - 2nd segment climb
  - EROPS/ ETOPS




Note: The actual internal and force balance geometry of the 22" rig is different from this early concept.

Figure 40.- ADP Interaction Rig

## Project Tasks and B&P Costs

As shown in Figure 41, this project comprises four major tasks. The fan flow path definition will come from the fan aero/acoustic design program, and the inlet, nacelle, and fan exit nozzle design and hardware will come from the Nacelle Aero Technology programs. A summary of the B&P costs to perform the suggested programs was presented to NASA and is provided as a separate attachment. The major tasks are briefly described below:

> Task 1 - Second Generation ADP Model: Mechanical Design and fabrication of the model, lubrication system, control console, instrumentation, (including rotating and skin balances) and integration with NASA's drive rig.
>
> Task 2 - Fan Performance Mapping Equipment: Mechanical Design and fabrication of fan mapping equipment (See Figures 42 and 43).
>
> Task 3 - NASA Drive Rig: Design, fabrication, and shakedown test of the new, more powerful drive rig at NASA Lewis.
>
> Task 4 - Rig Tests and Analyses: Interaction Rig tests in uninstalled configuration at NASA-Lewis and Pratt & Whitney analysis/test support.

Tasks 2 and 3 will be performed in conjunction with each other to ensure the model is compatible with the drive rig. Dynamic simulation of the whole model/drive-rig system will be performed to assure that no adverse coupled vibrational modes exists in the operating range. The model from Task 1 will be made available for shakedown of the system in Task 3. In Task 2, equipment (see Figure 43) required to obtain accurate fan speed-flow, surge margin and distortion tolerance data will procured. Task 4 will start after shakedown of the Interaction Rig has been successfully accomplished. After the first test, data will be analyzed and any necessary changes to the first design will be incorporated into the model for a second test. The design and hardware for the second test will be procured in Task 1.

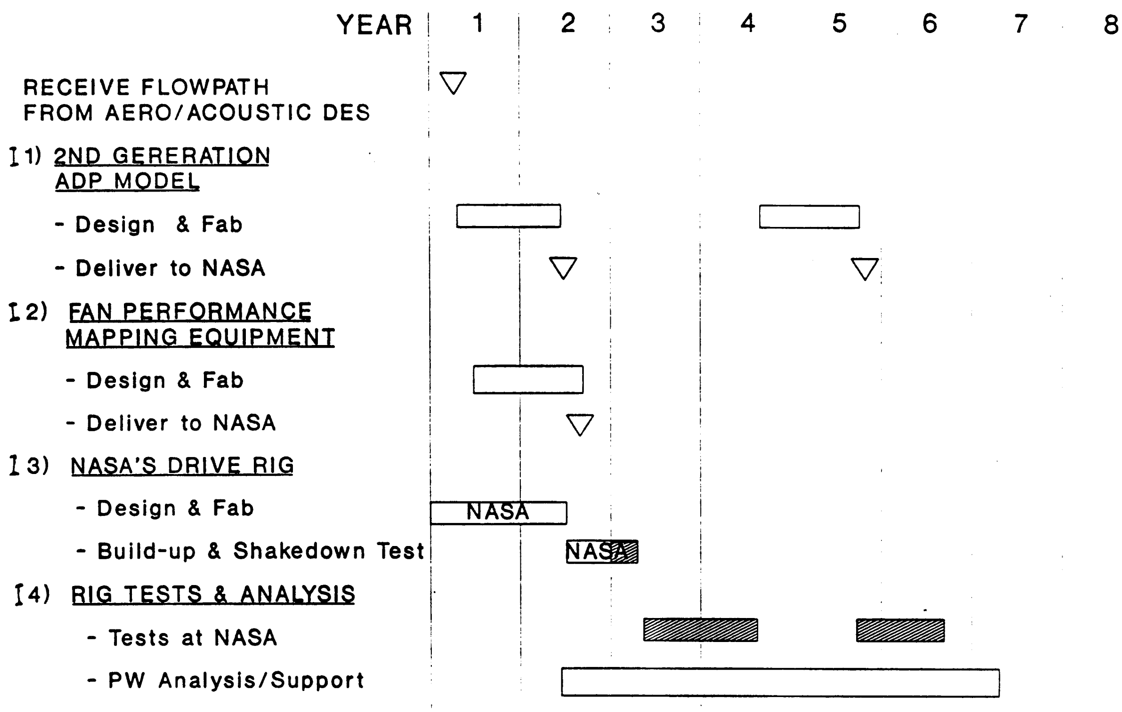



**Figure 41.- ADP Interaction Rig Program Schedule.**

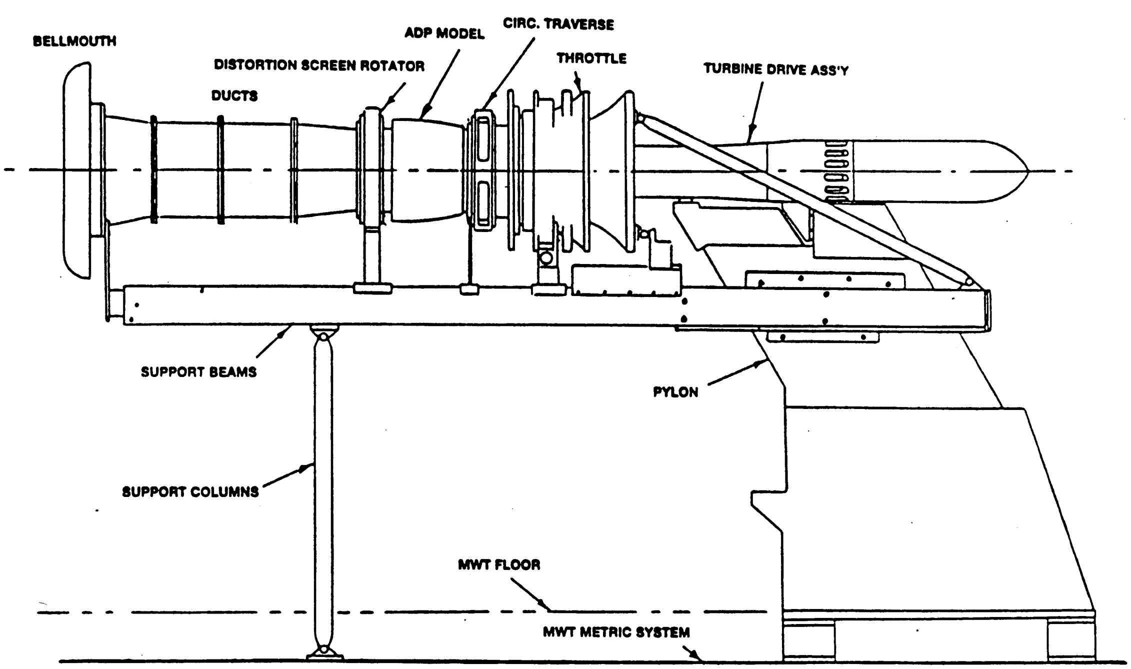



**Figure 42.- ADP Rig Installation for Fan Mapping Tests.**

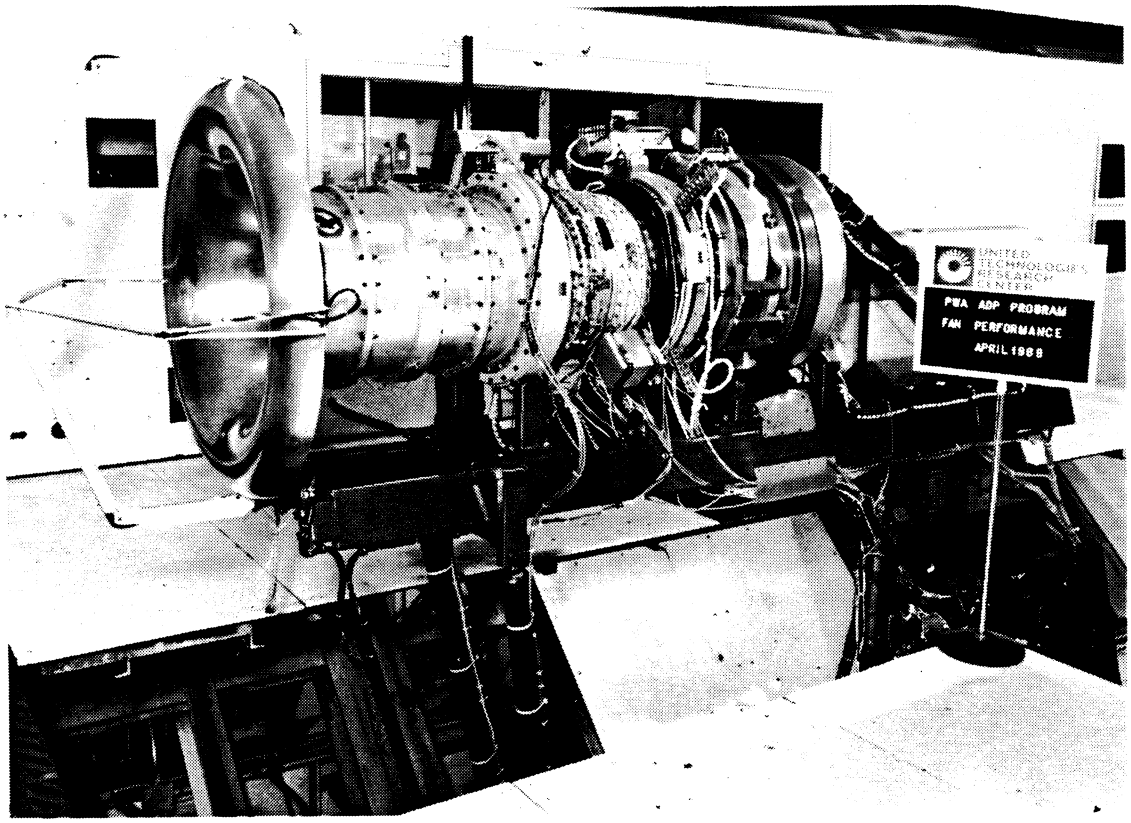



**Figure 43.- 17-Inch Model Drive Rig System for Fan Mapping Tests.**

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**13. ABSTRACT** ***(Maximum 200 words)***

A study was conducted to identify and evaluate noise reduction technologies for advanced ducted prop propulsion systems that would allow increased capacity operation and result in an economically competitive commercial transport. The study investigated the aero/acoustic/structural advancements in fan and nacelle technology required to match or exceed the fuel burned and economic benefits of a constrained diameter large Advanced Ducted Propeller (ADP) compared to an unconstrained ADP propulsion system with a noise goal of 5 to 10 EPNDB reduction relative to FAR 36 Stage 3 at each of the three measuring stations namely, takeoff (cutback), approach and sideline. A second generation ADP was selected to operate within the maximum nacelle diameter constrain of 160" to allow installation under the wing. The impact of fan and nacelle technologies of the second generation ADP on fuel burn and direct operating costs for a typical 3000 nm mission was evaluated through use of a large, twin engine commercial airplane simulation model. The major emphasis of this study focused on fan blade aero/acoustic and structural technology evaluations and advanced nacelle designs. Results of this study have identified the testing required to verify the interactive performance of these components, along with noise characteristics, by wind tunnel testing utilizing and advanced interaction rig.

**14. SUBJECT TERMS**

Noise; Fan; Nacelle; Tip-speed; Composites; Acoustics; Structures; Ducted-prop; Cycle; Engine noise reduction; Turbofan engines; Ultra-high bypass ratio; Aerodynamics; Aeroacoustics

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